A CONSTRUCTION EQUIPMENT MANAGEMENT GAME

A THESIS

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A CONSTRUCTION EQUIPMENT MANAGEMENT GAME

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TABLE OF CONTENTS

LIST OF TABLES

LIST OF ILLUSTRATIONS

SUMMARY

Problems of construction management cannot be solved by strictly analytical methods because of the highly variable and dynamic nature of construction projects. Traditionally, construction managers have been trained through actual experience on many projects. Construction management games are a means of providing students with valuable experience in construction management before they enter the construction industry. This thesis investigates the structure and development of construction management games focused on the specific area of management of construction equipment. To facilitate this investigation, an actual construction equipment management game is developed as an experimental vehicle. This development provides insights into the structure and development of construction equipment management games in general, which are presented here. These insights can be used to generate specific games as useful tools for teaching equipment management.

CHAPTER I

INTRODUCTION

In the modern construction industry, many complex machines and non-mechanized devices, referred to collectively as construction equipment, are used to aid in the performance of various tasks. Examples of construction equipment are cranes, bulldozers, and pumps. Certain types of construction projects, including dams, bridges, and highways, are normally built with methods which require extensive use of construction equipment. On such projects, both the cost and the duration of the project are directly affected by the management of equipment on the project.

Management of construction equipment to control cost and duration of a construction project involves the solution of highly variable problems in a dynamic environment. Any one project presents several types of equipment management problems. The proper type, size, and number of units of equipment must be determined for the project. The most advantageous financial basis for procurement of the selected equipment must be determined, either rental or purchase. Finally, the equipment actually procured must be assigned to the various activities of the project to achieve maximum utilization of that equipment. These three types of equipment management problems are complicated by two characteristics of construction management. First, every construction project is unique and presents different circumstances requiring different solutions from those used on any other project. Second, on any one project, management decisions must be made and, if necessary, revised in a dynamic environment. Many elements of this environment can greatly affect the project cost and duration, yet cannot readily be predicted or controlled. An example of such elements is weather. Thus, equipment management to control cost and duration of a construction project involves solution of various problems for a unique project within a dynamic environment.

The traditional system used in the construction industry for training project managers to solve construction management problems has some inherent disadvantages. Under this system, managers learn the skills of project management, including equipment management, through years of experience on many projects. The highly variable and dynamic nature of construction management problems referred to previously precludes the use of academic, analytic solutions. Instead, through repeated exposure to such problems and observation of the effects of various solutions on the cost and duration of projects, managers develop the ability to select solutions that will have desirable effects on a project. The experienced manager is thus able to control cost and duration on a project within a dynamic environment. However, this system of training by actual experience requires a student who wishes to become a construction manager to either spend many unproductive years gaining the necessary experience without making decisions, or expose himself to high penalties for wrong decisions made before he has gained sufficient experience. Thus the traditional system for training construction managers is disadvantageous to students of construction.

Several authorities have recommended construction management games as a means of providing students with some experience in construction management before they begin work in the industry, thus decreasing the time needed for training by actual experience. Such games present a student with a fictitious construction management situation, allow the student to make decisions, and generate realistic results based on the student's decisions. In particular, a game focused on construction project management allows the player to make management decisions for a fictitious project. Cost and duration of the fictitious project are generated in such a game from the decisions of the player and the effects of a simulated dynamic environment. If the game is properly structured, the player's decisions will affect cost and duration of the fictitious project in the same way that those decisions would affect an actual project in an actual environment. By observing the results of decisions in the game, the player gains experience that can be applied on an actual project. Thus through exposure to such games, the student can partially develop the skills of project management while still in school, decreasing the time required for training by actual experience.

Thus, in summary, management of equipment is important in many areas of construction, and, because of the variable and dynamic nature of construction, construction management games can be valuable tools for teaching the skills of construction management, including equipment management skills.

The purpose of this thesis is to study the structure and development of games which could be used to teach management of construction equipment. It is hoped that the insights from this study will be useful in generating actual construction equipment management games. Such games would then be valuable teaching tools, as explained above. The specific area of games to teach equipment management is studied because no such games have been developed to date in the literature. Thus this thesis can make a contribution to the area of construction management games.

The study presented here of the structure and development of construction equipment management games was performed by developing an actual equipment management game as an experimental vehicle. In the course of reducing to practice the concepts of game building, the author obtained the desired insights into the structure and development of equipment management games. This methodology, and the organization of the remainder of this paper, which follows the methodology, are explained in detail in Chapter II.

The study presented in this thesis represents specific research in an area well defined in the literature. The literature contains the work of three teams in the area of construction management games. Within this work the concept of construction management games is proposed, the usefulness of such games is defined, and several games are developed which indicate the general structure and some specific methods for such games.

Au and Parti first proposed the use of "construction planning games and construction management games" as "a useful tool for the education of young engineers."[1]* They defined the structure of such games as involving play by periods, with the player's decisions and a

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*See first page of Notes.

realistic simulated environment used to generate results. They also proposed two specific games. One game,[2] for foundation excavation, involves contract bargaining, engineering investigations, and planning and scheduling phases. The latter phase includes selection and assignment of shovel and hauler units to an excavation project.

Au and Parti also developed a game dealing with the flow of capital of construction firms.[3]

Scott and Cullingford developed a construction management game[4] focused on resource scheduling. In that game, the player is allowed to order materials and define labor and equipment pools for a simulated project. Results in the game are determined from player decisions and project characteristics.

Halpin and Woodhead developed a computerized game[5] Constructo, which focused on the management of labor on construction projects. The player of Constructo defines a project and assigns labor resources for the project. Project progress is determined both from player decisions, and from the effects of a simulated environment. The environment is dynamic, with a degree of randomness. Constructo is the only game to date which contains such an environment.

This thesis examines an area not treated in the literature. The type of construction equipment management game studied here bears some resemblance to the Foundation Excavation Game of Au and Parti, which also involves selection and assignment of equipment. However, the type of game this study anticipates goes into much greater detail in the range of types and sizes of equipment, the components of equipment costs, the financial basis for equipment procurement, and the effects of idle time on costs, than the Foundation game. The type of game studied here differs from both the Foundation game and the game of Scott and Cullingford in that it incorporates a dynamic environment including weather and equipment breakdowns. It differs from the dynamic environment game of Halpin and Woodhead in that it is focused on equipment rather than labor.

CHAPTER II

METHODOLOGY

In this thesis a study is made of the structure and development of games which could be used to teach construction equipment management. The best way found to make this study is to actually develop a construction equipment management game, for reasons explained below. Such a game is developed. The insights into construction equipment management games provided by the development of this experimental game are then presented to complete the study which is the purpose of this thesis.

The best way to study the structure and development of construction equipment management games is to actually develop such a game, for two reasons. First, since no previous work in this specific area exists, the study must involve extension of existing materials. Second, it is preferable to make such an extension in specific rather than general terms. This is because a construction management game requires fairly complex interactions among the components of the game. By developing a specific, workable game, it is assured that the concepts developed will actually permit such interactions. These concepts can then be extracted in general terms to provide insights into the structure and development of construction equipment management games. Thus, the best way to study the structure and development of construction equipment management games is to develop a specific game as an experimental vehicle.

Accordingly, an experimental construction equipment management game is developed in this thesis. This game is designed to provide the player with an experience comparable to the experience of managing construction equipment on an actual construction project. The game is specific and workable. It embodies the concepts developed by the author for construction equipment management games.

The insights into the structure and development of construction equipment management games provided by the development of the experimental game are presented to complete the study proposed for this thesis. For the experimental game, the author developed all the elements and relationships necessary for a construction equipment management game. By examining this process in retrospect from a general viewpoint, insights are gained into the entire area of construction equipment management games. The structure developed for the experimental game indicates desirable features for the structures of similar games. The process followed in developing the experimental game indicates useful procedures for developing similar games. These general insights are presented to satisfy the purpose of this thesis.

The remaining chapters in this paper are organized to follow the methodology explained above. Chapter III presents the specific experimental construction equipment management game developed for this study. All the specific components and relationships that compose the game are explained there. This should provide the reader with a knowledge of the experimental game sufficient to permit the understanding of the general insights obtained from it. Chapter IV presents the insights into construction equipment management games provided by the development of the experimental game. This completes the study proposed for this thesis.

CHAPTER III

AN EXPERIMENTAL CONSTRUCTION EQUIPMENT MANAGEMENT GAME

Introduction

This chapter presents the experimental construction equipment management game developed to study the construction equipment management gaming environment. The game is designed to provide the player with an experience comparable to the experience of managing construction equipment on an actual construction project. It is specific and workable. It embodies the concepts developed by the author for construction equipment management games. From this chapter, the reader should gain enough knowledge of this game to understand the general insights provided by its development, presented later.

To provide the player with an experience similar to that of managing construction equipment on an actual project, the experimental game presented here has the following basic structure. The player is presented with a fictitious project requiring extensive use of equipment, and a simulated environment surrounding the project. The player plans the use of equipment on the project. The simulated construction of the project then proceeds generated from player decisions and simulated environmental effects. Environmental effects disturb the player's plan of construction. The player attempts to offset these effects by proper equipment management to bring about the desired project cost and duration. Thus the player of the game gains the experience of managing construction equipment on a project within a dynamic environment.

The game consists of eight components which interact to provide a realistic management experience. The "Project Model" component presents the fictitious construction project for which the player will make equipment management decisions. The "Equipment Market" and "Union Hall" components simulate the equipment dealers and labor unions that would confront an actual project manager. The component, "Weather and Its Effects," provides realistic weather conditions to influence the course of the fictitious project. The component, "Cost and Breakdowns," is used to generate realistic costs and breakdowns for equipment on the fictitious project. Two components, "Weekly Networks" and "Forms," explain techniques of the game that enable the player to generate and record results during play. Finally, a "Sequence of Play" component provides step-by-step instructions for play which integrate the use of all other components with player decisions to produce the finished game. By following these instructions, the player can make equipment management decisions for the simulated construction project and generate realistic results from these decisions and the environment of the game.

The game in finished form as it would be presented to a player is given in Appendix A. The components of the game are explained below. Detailed information on the sources of the components is given in the Appendices.

The Project Model

The "Project Model" component of the game presents the fictitious construction project for which the player will make equipment management decisions. This project is the construction of a concrete girder river bridge, shown in profile in Figure 1. It requires extensive use of a variety of equipment. The "Project Model" has two parts. The "Project Description" gives qualitative information about the project, both finished product and general construction sequence. The "Activity Information" gives quantitative information on equipment requirements and durations of work on the project.

The "Project Description" gives qualitative information about the fictitious project which enables the player to relate the simulated use of equipment during the game to a realistic construction situation. There are illustrations and descriptions of the various features of the bridge to be constructed, including foundations, piers, abutments, and superstructure. There are also qualitative descriptions of a Critical Path network of activities* for the construction of the bridge. With this information, the player has a realistic picture of what will "happen" on the fictitious project and can relate quantitative activity durations and equipment requirements presented later to that picture. For example, one activity in the project which will be performed at each bridge pier, "Drive Steel Sheet Pile Cofferdam," is described as follows: "A steel sheet pile cofferdam is driven at the pier site to permit dewatering for pier construction. A barge delivers sheet piles to the site. A crane with a hammer sets and drives the sheeting. Work can be speeded by using a second crane to set and perhaps partially

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*See Antill and Woodhead[6] for basic information on Critical Path networks and activities. Generally, an "activity" is a distinct task within a project, with a readily identifiable beginning and ending; a Critical Path network establishes logical relationships between the activities of a project.

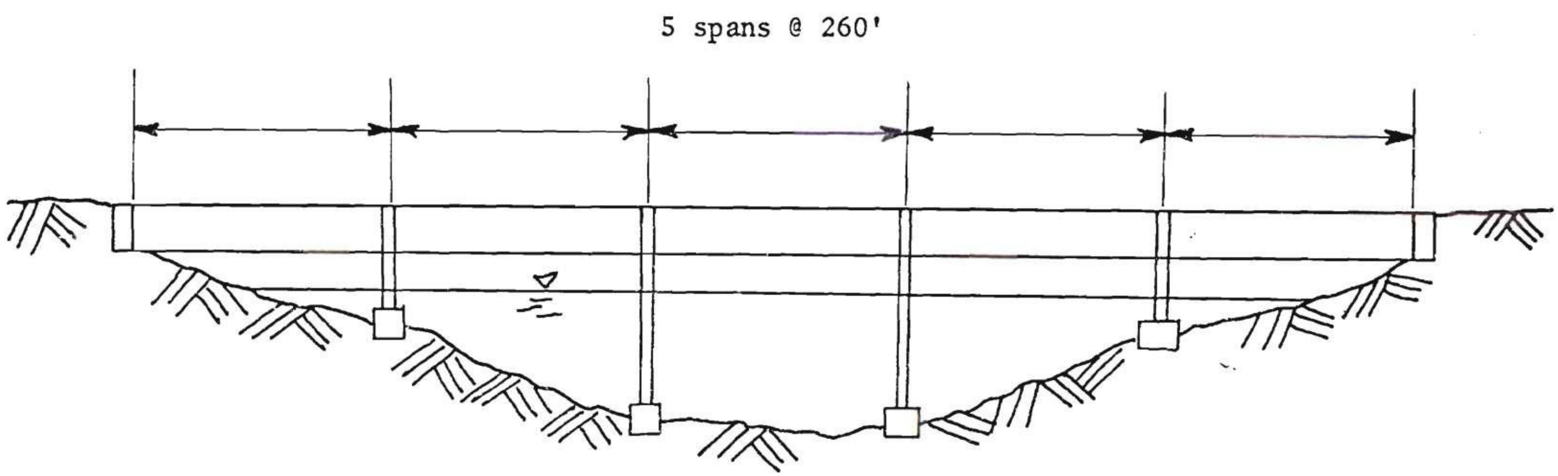


Figure 1. Bridge in Profile

drive sheeting." Later during the game, when the player assigns the required barge, barge propulsion unit, and floating crane with a hammer to this activity for a given duration, the player can relate these game manipulations to a picture of these equipment units actually driving a cofferdam for a bridge pier. Thus the player can regard the game as the management of equipment of an actual project.

The "Activity Information" gives quantitative information about each activity in the project Critical Path network. The player has a qualitative understanding of what the project network involves from the "Project Description." In the second part of the "Project Model," the project is quantitatively defined in terms of equipment usage. Minimum equipment requirements, and alternate sets of equipment, if any, that can be used on each activity are specified. For example, Figure 2 shows the basic equipment requirements and additional equipment that can be assigned given in the "Activity Information" for the project activity, "Drive Steel Sheet Pile Cofferdam." Also in the "Activity Information," methods are given for determining a basic duration of an activity given any set of equipment assigned to the activity. These durations represent how long the activity will take with assigned equipment under "good" conditions, that is, with no bad weather or equipment breakdowns. For example, Figure 3 shows the basic durations of the activity, "Drive Steel Sheet Pile Cofferdam," for two specific equipment assignments, as determined from the "Activity Information." Thus the player is given a project with equipment requirements and work durations for various equipment assignments.

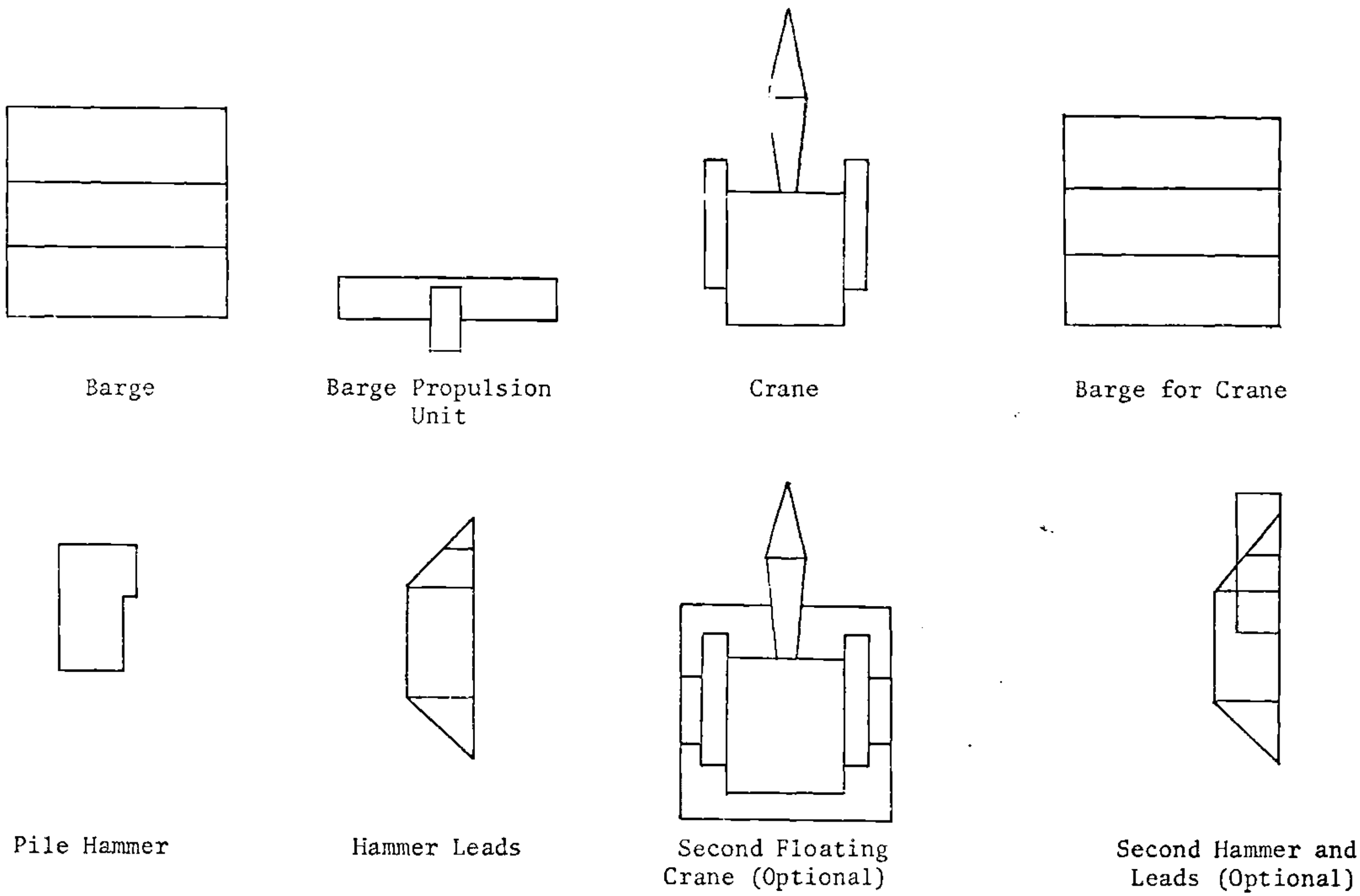


Figure 2. Equipment Requirements for "Drive Steel Sheet Pile Cofferdam" Activity

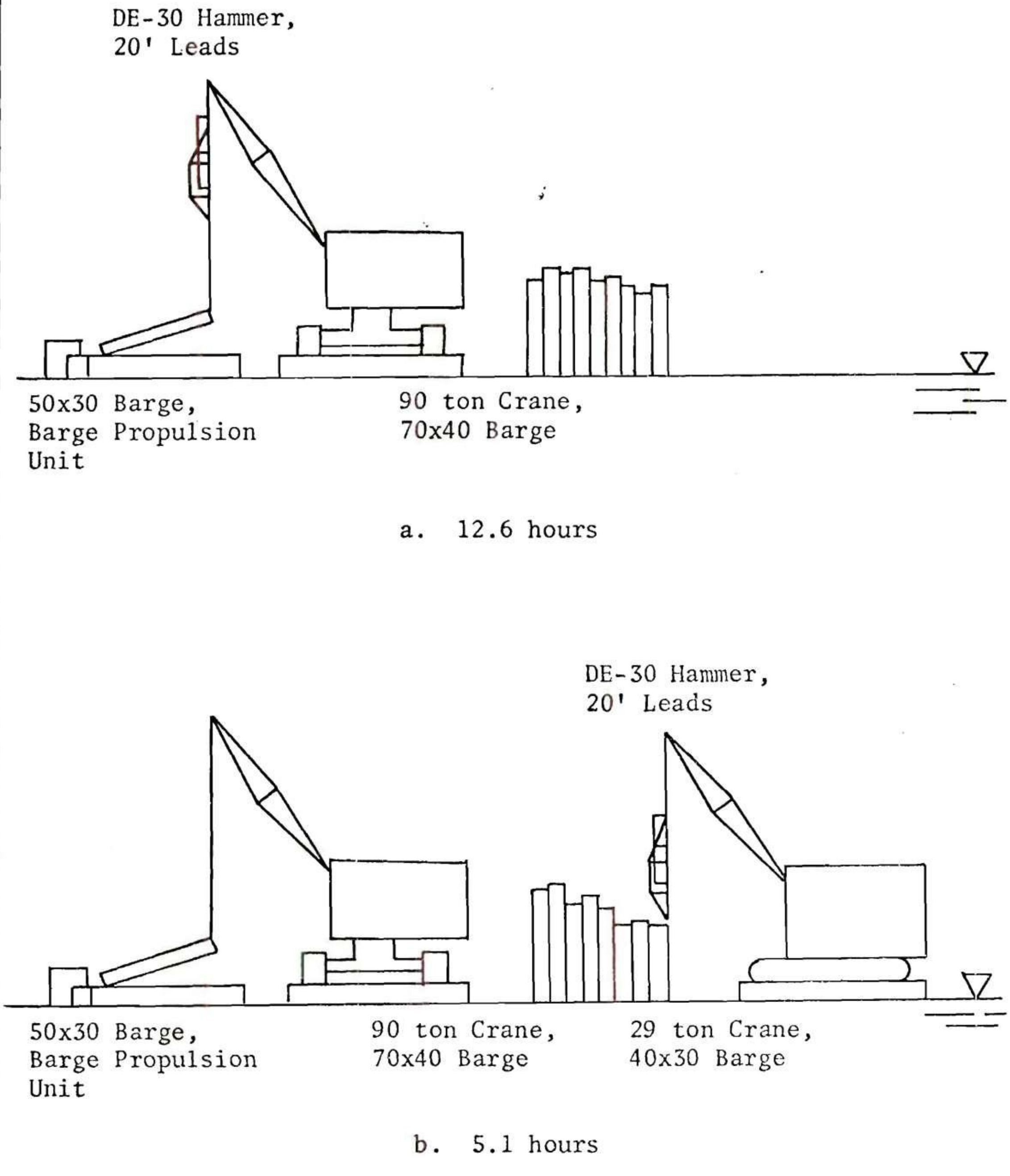


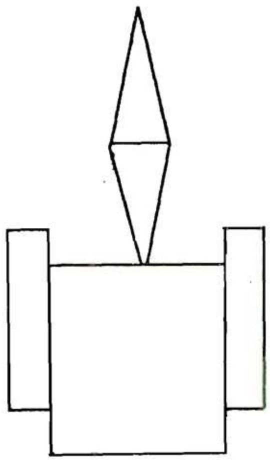
Figure 3. Basic Durations of "Drive Steel Sheet Pile Cofferdam" for Two Equipment Assignments

The Equipment Market

The "Equipment Market" component of the game is intended to simulate a possible market that would be available to meet the requirements and work durations for various equipment assignments. The player will "rent" or "purchase" all equipment needed on the fictitious bridge project from the Equipment Market. It includes a list of equipment units with specifications and cost information, and "market conditions" that describe the availabilities of various equipment for rent or purchase. A restriction on sale of equipment by the player is also included in the "Equipment Market."

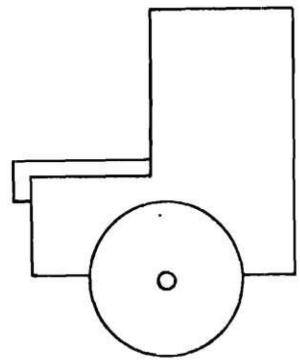
The list of equipment units includes specifications and cost information for all types of equipment required for the bridge project of the game. Ranges of size and type of units are provided where more than one could be used on the project. For each unit in the list, specifications are given which would be useful to the player during the game. Cost information for each unit in the list includes a price for new purchase, a price for used purchase, and rental rates. Figure 4 shows a few representative equipment units from the Equipment Market, with sample specifications and cost information.

The "market conditions" portion of the Equipment Market describes the availabilities of various types of equipment for rental or purchase. When the player wants to purchase new equipment or rent equipment, the only restriction on availability is a waiting period to fill the order. For example, the player must wait "six months" in the game for a new crane. Used equipment is made available on a limited basis through a "used equipment market" which is generated periodically in the game.



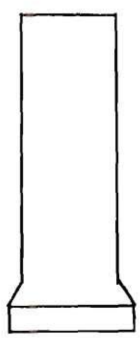
65 Ton Crane

172 Horsepower
Price $140,000
Rent per Day $346



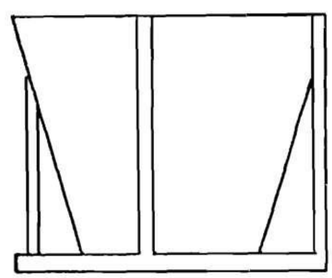
6" Centrifugal Pump

65 Horsepower
Price $4500
Rent per Week $91



DDDE-30 Pile Hammer

30100 Foot-pounds
50 Blows per Minute
Price $18,300



Concrete Bucket

1 cubic yard
Price $525
Rent per Day $12

Figure 4. Sample Equipment from Equipment Market

This used market contains, for example, two cranes for each "month" in the game.

A restriction on sale of equipment by the player is also included in the "Equipment Market." This restriction forces the player to retain any purchased equipment until all work on the project involving that type of unit has been completed. This arbitrary restriction is intended to prevent short-term usage of purchased equipment which would not occur on an actual construction project.

The Union Hall

The "Union Hall" component of the game presents the player with working rules and wage scales for equipment operators, simulating the situation of an actual project manager dealing with a union. The working rules for operators specify the operators required for various types of equipment, and rules for pay during overtime and idle time. The wage scales specify wages for all required operators. The player obtains operators for all equipment in the game based on this information.

Weather and Its Effects

The component of the game, "Weather and Its Effects," is used in the generation of results in the game to simulate the effects of actual weather on construction work so that realistic results will be generated from the player's decisions. This component includes simulated weather conditions which "occur" on the project, and techniques for calculating the effects of weather on the project.

The simulated weather conditions for the project are in the form of daily weather data. Daily average temperature, precipitation, and wind speed are given in a table for a period of two calendar years. The project of the game is "started" at some point in the two-year period. Weather conditions described by the data in the table following the project "starting" date are assumed to occur on the project.

The techniques for calculating the effects of weather on the project account for both losses of working time due to severe weather, and losses of productivity for work during unfavorable weather. If weather data indicate severe low temperatures or thunderstorms during some period of play, time available for work is decreased in that period. For example, no work is possible on a day when wind chill temperature is below 0°F. If weather data indicate less severe, but unfavorable, weather during a period of play, productivities are reduced on work done in that period. For example, a steady rain of 0.5 inches during a day would decrease productivity to 92 percent of normal. These techniques are given to the player in the form of step-by-step calculations.

Cost and Breakdowns

The "Cost and Breakdowns" component of the game contains techniques and tables which are used to generate realistic costs and breakdowns for the equipment the player decides to employ in the game. The techniques can be divided into techniques for generation of ownership costs, techniques for generation of operating costs, and techniques for generation of duration and cost of breakdowns. A summary of costs is also given to enable the player to readily calculate cost and breakdown information for any unit of equipment.

Ownership costs are calculated in the game as fixed weekly charges which are incurred for all equipment the player has procured regardless of how much time the equipment is working. These costs include depreciation and interest, insurance, taxes, and storage. They have been calculated using standard methods and assumptions, and are tabulated for the player.

Operating costs are calculated in the game as hourly charges which are incurred for a particular piece of equipment only during the hours when it is working. These costs include fuel, oil, and maintenance and minor repair costs. They have been calculated using assumed cost rates for each horsepower-hour of work, and are given in a table.

Duration and cost of breakdowns are generated for equipment in the game using probabilities of breakdowns with random number trials,* and cost rates for breakdowns that do occur. Two types of breakdowns are possible in the game. Large breakdowns in the game simulate actual breakdowns that would require removal of equipment to a shop. Small breakdowns in the game simulate actual breakdowns that could be repaired in the field. The player is given a table of probabilities of large and small breakdowns occurring for a given unit of equipment on an activity of given duration. For each unit of equipment on each activity during the game, the player makes random number trials using the probabilities from this table to generate occurrence of breakdowns.** In another table the player is given cost rates for breakdowns that do occur, which

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*See immediately below for information on random number trials.

**See "Sequence of Play" component for detailed explanation of the procedure for making Random Number Trials (Appendix A).

are used to calculate the total cost of any breakdown.

A summary of costs is given in the "Cost and Breakdowns" component to enable the player to calculate cost and breakdown information for any unit of equipment. For new, used, or rented equipment of any type, the applicable cost rates and breakdown probabilities are listed, and tables containing that information referenced.

Weekly Networks and Forms

The components, "Weekly Networks" and "Forms," explain techniques of the game which are used to generate and record results. The game is played in periods, with each period representing a calendar week on an actual project. For each period, a weekly critical path network is used to model player decisions and serve as a framework for the interaction of other components in the generation of results. Decisions and results of play are recorded on special forms designed for the game. In "Weekly Networks" and "Forms," the player finds explanations of these techniques which are helpful in applying them.

Sequence of Play

The "Sequence of Play" component provides step-by-step instructions for playing the game. These instructions integrate the use of all other components with player decisions to produce a realistic equipment management experience. There are two parts to the "Sequence of Play." By following Part I, "Project Planning," the player plans the use of equipment for the project of the game. Thereafter, the game is played by periods. Each period represents a calendar week on an actual project. By following Part II, "Play for a Period," for successive periods, the player makes equipment management decisions for the project and generates results on the project from those decisions and simulated environmental effects.

Part I of the Sequence of Play, Project Planning, represents the planning phase of an actual construction project. The player follows these instructions only at the start of the game. The player is directed to produce a plan for equipment procurements and assignments on the fictitious bridge project that will permit completion within an assigned time limit at lowest possible cost. The Project Model, Equipment Market, Union Hall, Weather and Its Effects, and Cost and Breakdowns components provide the player with all information that would normally be available to an actual project planner. For example, the Project Model provides activity equipment requirements and basic durations that an actual planner could obtain from a project estimate. The player can use any of a large number of planning techniques actually used in practice, such as network compression analysis. Thus by following the instructions in Part I of the Sequence of Play, the player gains a realistic experience in planning a construction project.

Part II of the Sequence of Play, "Play for a Period," is intended to place the player in the position of equipment manager on an actual project, making decisions and observing the results of those decisions on a week-to-week basis. After initial planning, the game is played by periods, with each period representing an actual calendar week. The player follows the instructions in "Play for a Period" during each period. This leads the player to make equipment management decisions for the period, and then to utilize all other components of the game to generate and record the results of those decisions on the project. There are six steps in "Play for a Period." Figure 5 shows how player decisions and components of the game interact in each step.

In step one of "Play for a Period," as shown in Figure 5, the player makes weekly equipment management decisions based on the plan developed in Part I, previous results, and the Project Model and Equipment Market Components of the game. These decisions include what activities will be worked, how equipment will be assigned to activities, and whether to work extra hours during the week. The player compares the plan from Part I with the results of play from previous periods. If the project is proceeding according to plan, then the decisions can be made as planned. Probably, however, environmental effects will have disturbed the plan during previous periods. In this case, the Project Model and Equipment Market components will provide alternative courses to remedy the situation, such as procuring and using an extra crane to make up for lost time. Thus the player will evaluate project progress and make decisions to bring about desirable results.

In step two, as shown in Figure 5, the player generates a "basic weekly network" for the period from the weekly decisions of step one and the Project Model component of the game. All scheduled activities and equipment assignments are known from the weekly decisions. The Project Model component provides logical connections between activities, and basic durations for the activities given assigned equipment. From this the player can develop a basic weekly network which essentially is a model of what will occur on the project under the player's decisions if no adverse conditions affect the work.

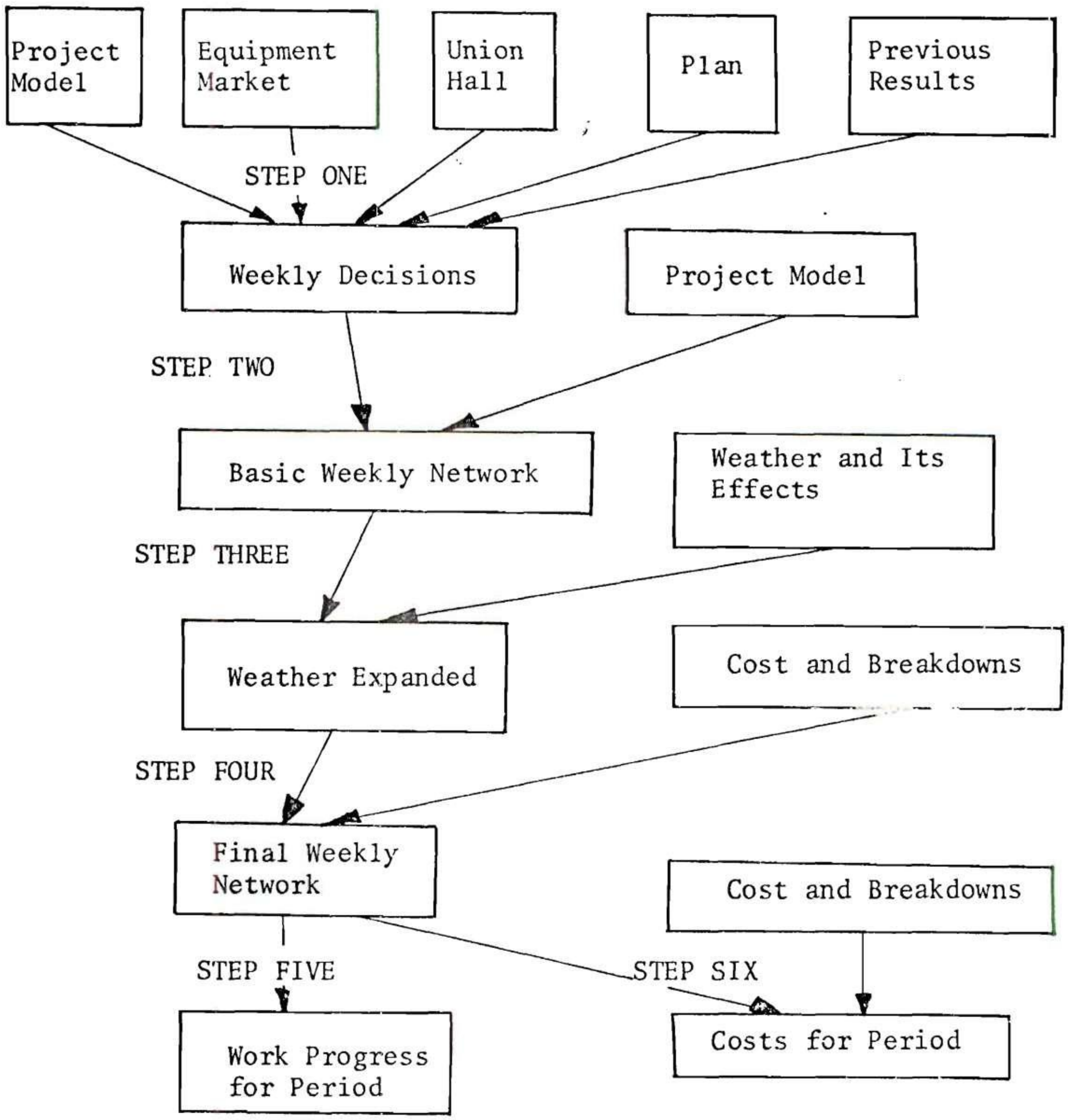

Figure 5. Play for a Period in Sequence of Play

In step three, as shown in Figure 5, the player combines the basic weekly network model with information from the "Weather and Its Effects" component to produce a weather expanded weekly network. This involves determining simulated weather for the period and the effect of that weather on the activities scheduled for the period. The weather expanded network becomes a model of what will occur on the fictitious project given player decisions and simulated weather.

In step four, the player adds the effects of equipment breakdowns, as determined from the Cost and Breakdowns component, to the weather expanded weekly network to produce the final weekly network for the period. This network now models what will occur on the project given the player's decisions and the simulated environment of the game.

In step five, work progress for the period is determined from the final weekly network by simple calculations, and recorded.

In step six, costs for the period are determined from the final weekly network and the Cost and Breakdowns component, and recorded.

Thus, by following the steps in Part II of the Sequence of Play for successive periods, the player can make equipment management decisions for a simulated construction project in a realistic simulated environment, and generate the cost and duration of the project that result from these decisions.

An Example of Play

An example of play of the game indicates the type of experience the game provides. For the example, a time limit of 12 periods, that is, 12 simulated weeks, was set for completion of the fictitious bridge construction project of the game. The project was "started" in October, 1973, to run through December, 1973. A project plan was developed to meet the time limit at lowest possible cost. The plan involved constructing both sides of the bridge concurrently, and purchasing only equipment which could be fully utilized over extended periods. The fleet of equipment purchased for the example is shown in Figure 6. All other equipment requirements were met by rentals. As play proceeded through the first nine periods, the plan worked well.. There were some minor delays due to breakdowns, worsening weather, and insufficient equipment. But time saving work methods made possible by adroit equipment assignments kept the project ahead of schedule. However, during the final three weeks of play two crippling breakdowns followed by bad weather delayed progress so that the project could not be finished on time. The plan had worked well for minimizing costs through full utilization of purchased equipment. Figure 7 shows the percent utilizations achieved for the two most expensive units, the 90 ton cranes, which are seen to be good. But the plan did not allow enough safety margin in scheduling to account for decreasing productivities due to weather, which are shown in Figure 8. Thus in this example the game provided experience particularly in equipment assignments and weather effects.

Full details of this example are given in the Appendix.

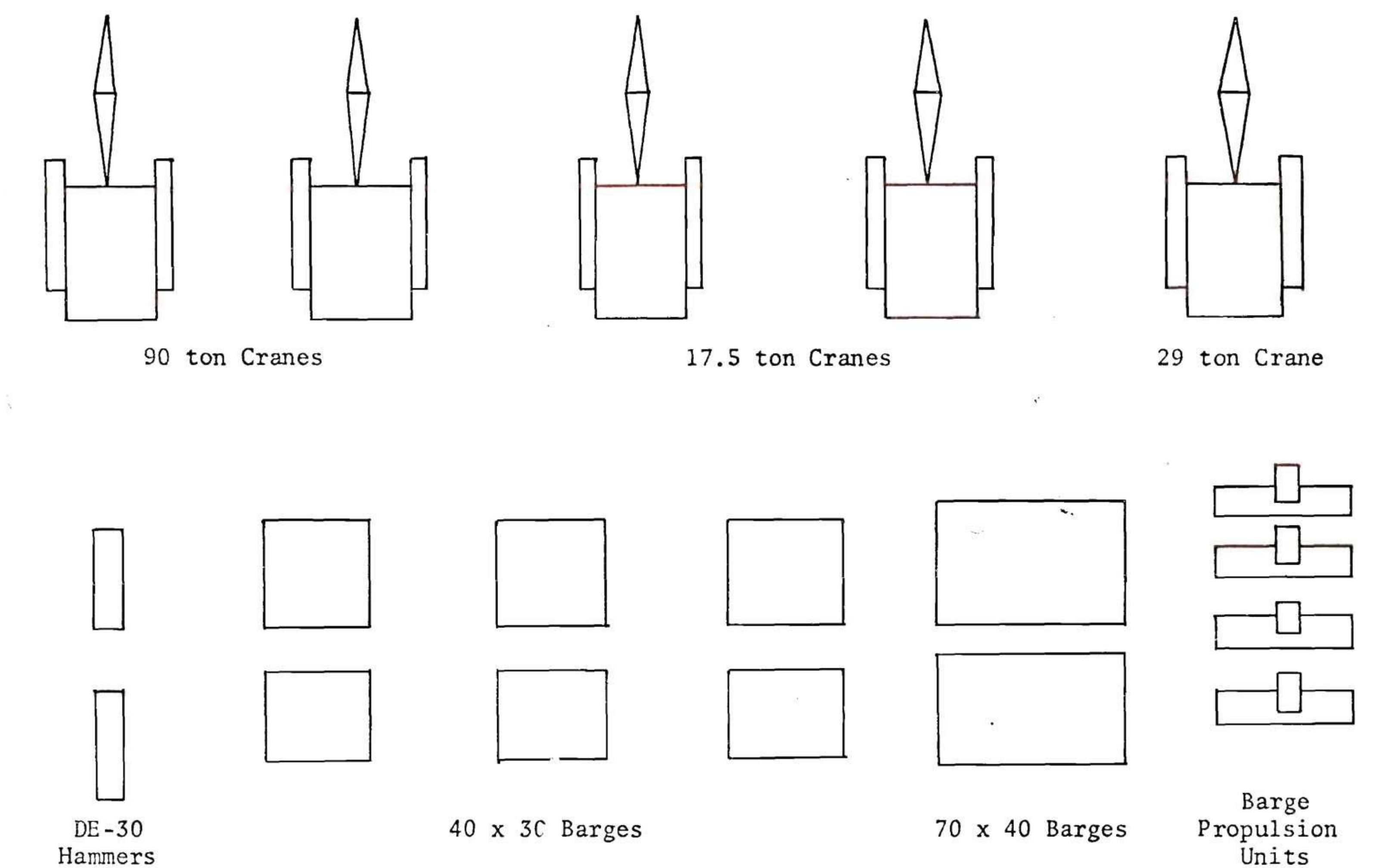

Figure 6. Equipment Purchased for Example

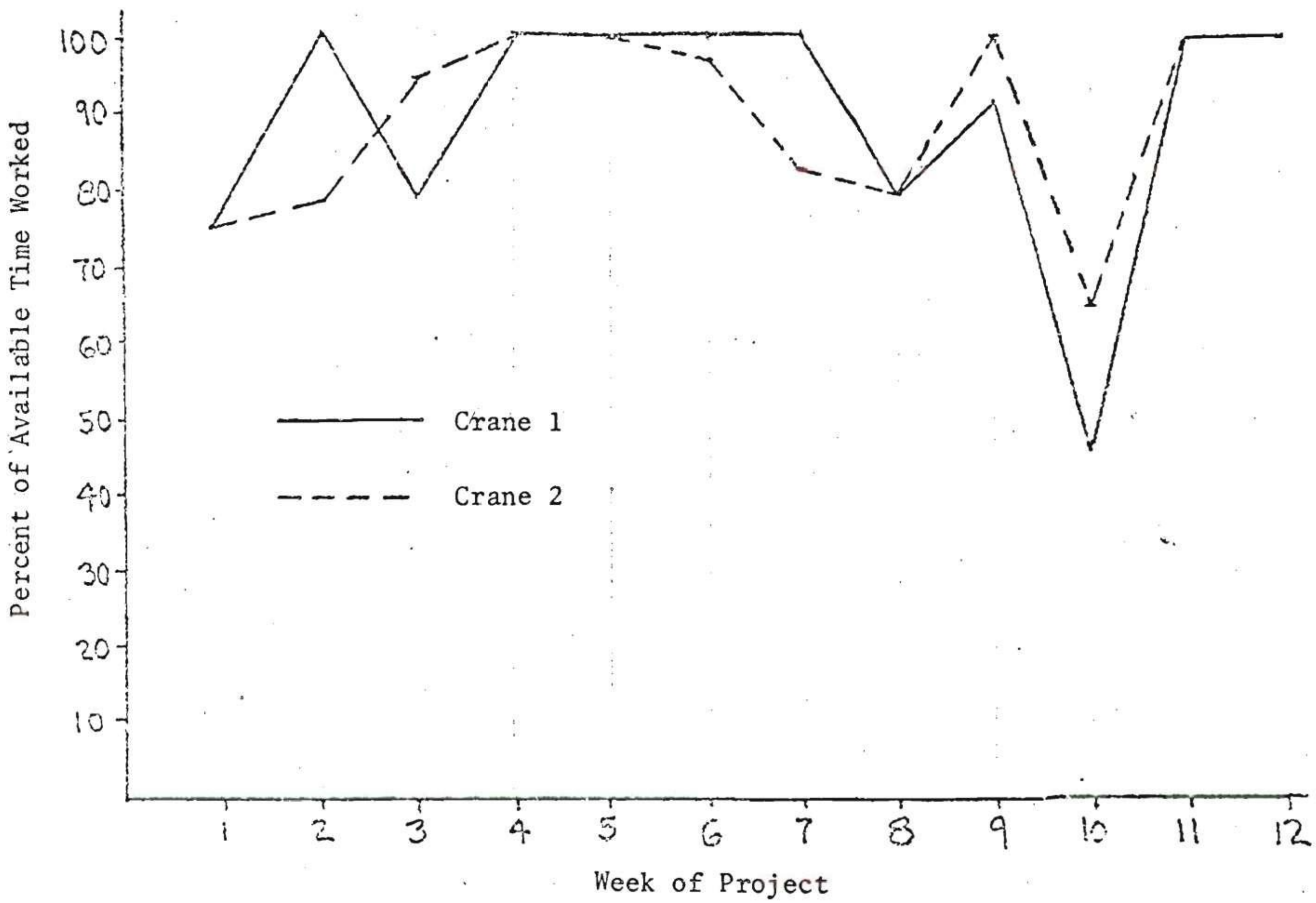

Figure 7. Utilization of 90-ton Cranes in Example

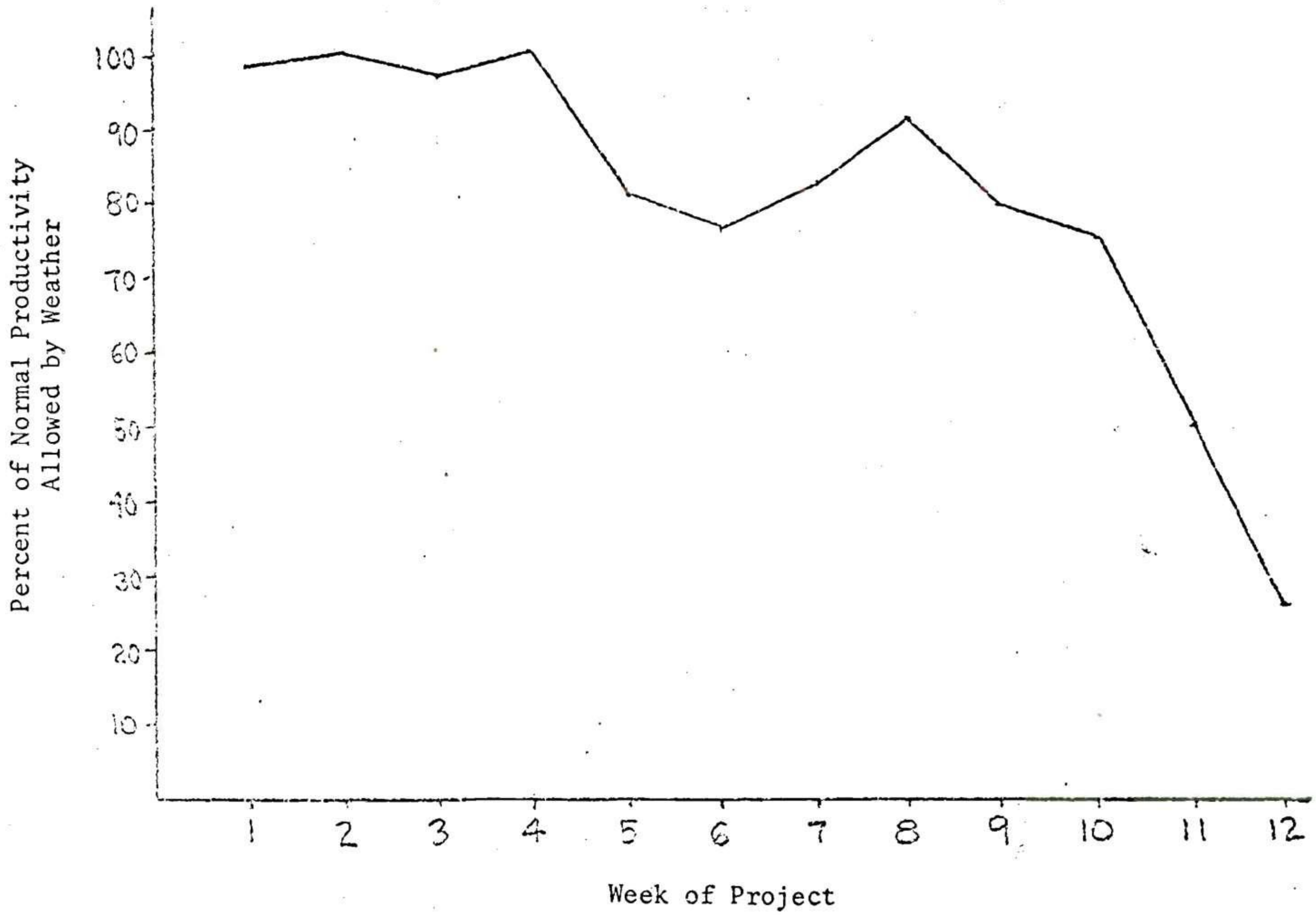

Figure 8. Effect of Weather on Productivities in Example

CHAPTER IV

THE STRUCTURE AND DEVELOPMENT OF CONSTRUCTION EQUIPMENT MANAGEMENT GAMES

Introduction

This chapter presents the insights into the structure and development of construction equipment management games provided by the development of the experimental game presented in Chapter III, completing the study proposed for this thesis. In order to present these insights in an orderly and comprehensive manner, the discussion is organized around certain elements which are common to most project management games. These elements are briefly introduced in the next section. Then each game element is examined in detail in a separate section. In the first part of a given section, the general nature of the game element dealt with in that section is explained. Examples of this element from one or more of three existing project management games* are used to clarify this explanation. In the second part of the section, the development of this element for the experimental construction equipment management game presented in Chapter III is examined. This provides insights into the structure and development of this particular element for construction equipment management games in general. All of

*These are the foundation excavation game of Au and Parti, Scott and Cullingford's scheduling game, and Halpin and Woodhead's Constructo. See Chapter I for a general explanation of these games.

the important elements of project management games are examined. Thus this chapter provides insights into the structure and development of all important elements of construction equipment management games, completing the study which is the purpose of this thesis.

Elements of Project Management Games

There are certain elements which are common to most construction project management games, around which the discussion of equipment management games presented in the next sections is organized. First, such games have the following components or models:

(1) Decision Model

(2) Project Model

(3) Resource Model

(4) Environmental Model

The decision model specifies the decisions a player is allowed to make in the game. The project model presents a framework or structure within which the simulated project is defined and within which the player will implement his management strategy. The resource model defines the management controlled entities or resources which the player can bring to bear and manipulate in order to effect the progress of the project. The environmental model provides a simulated environment to affect the course of the game's project.

Second, project management games have similar structures, with two phases of play:

(1) Initialization Phase

(2) Period Play Phase

The Initiliazation Phase involves establishment of a project plan and goals for the game. The Period Play Phase involves simulated construction of the game's project through successive periods representing intervals of calendar time.

Thus, six different elements are common to most project management games: four models and two phases of play. Together these elements constitute a complete project management game. These elements will now be explained in greater detail, and the development of these elements for the experimental game presented in Chapter III will be examined to provide insights into the structure and development of these elements in construction equipment management games in general.

The Decision Model

The Decision Model in a project management game specifies the decisions the player is allowed to make in the game. This determines the focus of the learning experience the game can provide, since the player will gain experience in the game through making decisions and observing their effects. Three existing games exemplify the relation between the focus of a game and its Decision Model. The foundation excavation game of Au and Parti focuses on planning for excavation. So the player is permitted to select sizes of shovels and haulers, and to assign the shovels to various excavation zones and the haulers to various routes. In Scott and Cullingford's game of project resource scheduling, the player can select labor and equipment pools for a project, order materials at various times, and establish priorities for the working of project activities. In Constructo, which focuses on management of labor, the player can select and assign labor resources for a project. The learning experience is expanded in the last game by allowing the player to make decisions not directly related to labor. These include options to start or stop activities, work overtime or holidays, or alter the weather sensitivity of activities. Thus the focus of project management games is determined by the decisions permitted in the Decision Model.

A study of the development of the Decision Model for the experimental game presented in Chapter III provides insights into the structure and development of Decision Models for construction equipment management games in general. The Decision Model of the experimental game is incorporated in the "Sequence of Play" component. The game is intended to provide a learning experience in the area of management of construction equipment for a single project. So the player is allowed to make decisions on manipulation of equipment. These include selection of type, size, and number of equipment units for a project; selection of rental or purchase as a basis for procurement of equipment; and assignment of equipment to activities on a project. Extending the results of this development to construction equipment management games in general, it can be said that Decision Models for such games should similarly reflect the learning experience which the games are intended to provide. If the focus is on management of equipment for one project, then a Decision Model identical to that of the game presented in Chapter III could be used. If a slightly different learning experience is desired, the Decision Model should permit different decisions to reflect this. For example, a decision on altering weather sensitivities of activities could be included in an equipment management game to provide the player with experience in that area, as in Constructo. Thus the development of the Decision Model of the experimental game indicates how Decision Models of construction equipment management games in general should reflect the learning experience the games are intended to provide.

The Project Model

The Project Model in a construction project management game presents the simulated construction project that the player will manage. This project is structured so that the course of simulated construction will be influenced by the type of decisions the player can make, as specified in the Decision Model. The Project Model can be established for the player in the game, or established by the player. The example games considered here include both types, and show how the Project Model is made sensitive to player decisions. In the foundation excavation game, the Project Model is established for the player. It includes sizes of excavations, and a map showing excavation and dump sites and travel routes and speeds. So the player's selections and assignments of shovels and haulers will directly affect the time needed for making the required excavations and hauls of material. In the games of Scott and Cullingford and Halpin and Woodhead, the Project Model is established by the player within a framework provided by the game. The player of the scheduling game defines a Critical Path network of activities,* each having requirements for labor, equipment, and materials. Simulated progress is then sensitive to player-established resource pools and work priorities. In Constructo, the player defines a network

*See note, p. 11.

of activities with a basic work crew for each. The rate of work on any activity is then sensitive to the amount of labor assigned to it by the player. Thus in project management games, the Project Model presents a simulated construction project which is sensitive to player decisions.

An examination of the development of the Project Model for the experimental game presented in Chapter III provides insights into the structure and development of Project Models for construction equipment management games in general. The Project Model of the experimental game is its "Project Model" component. This component is intended to present a project sensitive to player decisions on selection and assignment of equipment. The form developed to do this is a Critical Path network of activities, with alternate sets of equipment that can be assigned to each activity and a method of determining the duration of each activity for any set of equipment. As a general insight from this experiment, it can be said that the same form is suitable for Project Models of other construction equipment management games, that should be sensitive to equipment management decisions. In structuring a Project Model in this form, there are several methods which could be used to determine activity durations given any set of assigned equipment. First, durations may be directly determined from assigned equipment by simple relationships, as is done in the game presented in Chapter III in the "Activity Information" section of the "Project Model." Second, each activity may be structured as a simulation model, with durations determined from a simulation using assigned equipment. A unique model could be used for each activity, such as the model in Au and Parti's excavation game. There is also a general construction simulation technique[7] which could be used to produce activity models responsive to equipment assignments. All these methods can be successfully used. Thus the development of the Project Model of the experimental game indicates a useful form for Project Models of construction equipment management games in general.

The Resource Model

The Resource Model of a project management game specifies the resources that the player can manipulate for the simulated project. These are the resources focused on in the Decision Model. Au and Parti in their excavation game specify different sizes of shovels and haulers, with varying characteristics and costs. Scott and Cullingford specify required labor, equipment, and materials with costs for their scheduling game. Halpin and Woodhead in their labor game specify different building trades with wage rates.

The resource Model of the experimental game provides insights into Resource Models of similar games. The Resource Model of the game presented in Chapter III includes the "Equipment Market" and "Union Hall" components. Equipment units and equipment operators are specified in detail to correspond with requirements from the "Project Model" component. As a general insight, the Resource Model of any equipment management game should similarly specify equipment units and operators to meet requirements of its Project Model.

The Environmental Model

The Environmental Model in a project management game provides a simulated environment which affects the course of the project in the game. This environment is beyond the player's prediction or control, and so forces the player to continually reevaluate his plans as in actual construction. Constructo is the only game considered here that includes such an environment. It has three parts. Simulated weather is provided which affects the time available for simulated construction, and productivities during simulated construction. A variable economic index affects non-labor costs in the game. Finally, there is a random variation in activity durations to account for errors in estimated values presented to the player.

The development of the Environmental Model for the experimental game provides insights into the structure and development of Environmental Models for construction equipment management games in general. The game presented in Chapter III includes a two part Environmental Model, simulating two important influences on construction requiring extensive use of equipment. First, the "Weather and Its Effects" component provides simulated weather that influenced the game's project. Second, the "Cost and Breakdowns" component provides simulated equipment breakdowns which affect the simulated project. In general, it can be said that Environmental Models of equipment management games should include the important effects of weather and equipment breakdowns as the experimental game does. Weather effects can be simulated using weather data and estimated influence factors, as is done in the experimental game. Breakdowns can best be simulated using the techniques developed for the experimental game. These can be applied to any equipment with a known service life and hours worked per year. Thus the development of an Environmental Model for the game presented in the previous chapter provides techniques for generating Environmental Models of construction equipment management games in general.

The Initialization Phase of Play

The initial phase of the typical two-phase structure of project management games involves establishment of goals for the game and a project plan to meet those goals. The player can then measure progress toward goals during simulated construction by comparison with the plan. Two of the example games contain such a phase. In the initial phase of Scott and Cullingford's game, the player establishes a planned sequence of activities with labor, material, and equipment requirements. The goal of the game, the desired project duration, is set by this plan. In Constructo, the initial phase of play involves establishment of a network of activities with labor requirements. From this the game generates goals of time and cost limits for the simulated project, and a detailed planned activity schedule which meets those goals. In both games, the player compares cost and work progress at different stages of play with planned values to assess project status. Thus the initial phase of project management games involves establishing goals and a plan to meet the goals.

The initial phase of the experimental game developed for this thesis provides insights into the structure and development of initial phases for similar games. In the experimental game, this initial phase is the "Project Planning" section of the "Sequence of Play." A project duration is given to the player as a goal. The player produces a plan to meet this goal at lowest possible project cost. The plan includes major equipment purchases and assignments. When extending this development to the general case, the same form need not be followed. For instance, in similar games goals of cost and duration could be generated automatically from the Project Model as in Constructo, without further player decisions. However, the plan produced in the initialization phase of equipment management games should include major equipment purchases and assignments, as in the experimental game. This is because such decisions greatly affect the cost and duration of a project requiring extensive use of equipment. Thus the initial phase of the game presented in Chapter III indicates requirements for developing and structuring initial phases of similar games.

The Period Play Phase of Play

The second phase of project management game is simulated construction of the game's project through successive periods representing intervals of calendar time. The sequence of events in each period follows a general pattern. First, the player compares the results of simulated construction in previous periods to the plan from the initial phase of play, and reviews the decision options open within the game's environment. The player then makes period decisions to bring about desired results in the project. Finally, the simulated construction is advanced for the period through techniques for producing work progress and costs from interaction of game models. The game ends when a number of periods equal to the project duration limit have been played. This sequence is followed in Scott and Cullingford's game and Constructo, using periods representing calendar months. Of particular interest are the techniques used for generating period work progress and costs in these games. In any period of Scott and Cullingford's game, the resource requirements of activities in the Project Model are met with the resources in the Resource Model as permitted by the resource pools and activity priorities established by player decisions from the Decision Model. All possible work proceeds, after which work progress is calculated from the network. Costs for the period are calculated from the established resource pools using fixed cost rates per period for all labor and equipment. In Constructo, the Project Model also establishes a basic activity network. All activity durations are sensitive to the number of workers assigned to them, so that player decisions on assignments of labor from the Resource Model affect the basic network. The Environmental Model also affects the basic network. The network is then used to calculate work progress. Costs are calculated from this using labor wages for all labor performed and indirect costs apportioned over activities. Thus, the second phase of project management games is simulated construction of the game's project through successive periods, with cost and work progress calculated for each period from interaction of game models.

The development of the second phase of the experimental equipment management game presented in the previous chapter provides insights into the structure and development of this phase for construction equipment management games in general. In the experimental game, the second phase of play is included in the "Play for a Period" section of the "Sequence of Play" component. The game is played in periods representing calendar weeks. For each period, the player reviews progress and makes decisions, as in most project management games in this phase.

Work progress and costs are calculated for any period in the experimental game from the interaction of game models. An activity network, with basic activity durations, is established for any period by the Project Model and resource assignments made by the player from the Resource Model. The Environmental Model then acts on activity durations. Period work progress is calculated from the network. Costs are calculated using the network and equipment cost rates from the "Cost and Breakdowns" component of the game. As a general insight, the second phase of other construction equipment management games can be structured after that of the experimental game. The standard analysis and decisions by the player should begin this phase of equipment management games, as they do in the experimental game and most other project management games. Then the techniques developed for the experimental game for calculation of period work progress using networks, and calculation of period costs using equipment cost rates, can be employed in equipment management games. These techniques are general and will generate realistic results in any equipment management game. Thus the development of the second phase of the experimental game provides a model for the structure and development of the second phase of similar games.

Conclusions

In summary, the development of the experimental game presented in Chapter III provides the following insights into the structure and development of construction equipment management games:

1. In construction equipment management games, the player should be permitted to make decisions on selection, assignment, and financial basis of procurement of equipment.

2. Construction equipment management games should be based on a project model which is sensitive to selection and assignment of equipment.

3. Construction equipment management games should include an Environmental Model to simulate the important effects of weather and equipment breakdowns on construction requiring extensive use of equipment.

4. Construction equipment management games should include an initial planning phase followed by simulated construction through successive periods representing intervals of calendar time.

5. The plan produced in the initial phase of construction equipment management games should include major equipment purchases and assignments.

6. The techniques used in the game presented here for calculating work progress and costs for simulated construction are suitable for equipment management games in general.

Recommendations

Three extensions of the type of game considered here are suggested.

First, such a game as has been considered here would be improved if it were computerized. This would involve programming all relationships used to generate results and designing methods for input of player decisions and output of project results. Then the arithmetical calculation required by the game in its present form, which adds little to the learning experience, could be eliminated. The player would also be prevented from closely examining the relationships used in the game in an attempt to "beat the game" rather than applying sound management techniques.

Second, an equipment management game focusing on an entire firm's equipment rather than equipment for a single project could be useful. Such a game would present a player with varying equipment requirements on several "projects," which the player would have to meet at lowest possible cost. The emphasis would be on financial basis of procurement, maintenance, and replacement decisions taking into account economic life of equipment and obsolescence.

Finally, a game integrating management of labor, equipment, and materials on a single project, with a dynamic simulated environment, would be a most useful teaching tool. Perhaps this could be accomplished by specifications of alternate sets of equipment for each activity, with base durations for each; and functional relationships describing how alteration of labor crews would affect those base times. Materials deliveries would either permit or prohibit any activity, but not affect productivities.

APPENDICES

APPENDIX A

COMPLETE GAME FOR PLAYERS

Introduction

In this game you will act as equipment manager on the construction of a river bridge. You will plan the construction of the bridge and control the project as it proceeds. The final project cost and duration will depend on your decisions.

The game has eight basic components:

1. The Project Model tells you what work must be done on this project, what equipment can be used to do the work, and how long the work will take under "good" conditions. The "Project Description" section of this component contains qualitative information to familiarize you with the project. The "Activity Information" and "Miscellaneous Information" sections contain quantitative information for play.

2. The Equipment Market gives specifications, prices, and availabilities of various types of equipment that you can procure for the project.

3. The Union Hall gives working rules and wage scales for equipment operators for the project.

4. Weather and Its Effects gives weather that occurs on the project and techniques you will use to determine how weather affects work on the project.

5. Cost and Breakdowns contains tables that you will use to generate the costs and breakdowns incurred by the equipment you have

procured for the project.

6. Weekly Networks explains the framework within which you will calculate results from the interaction of the other components and your decisions.

7. Forms explains the forms on which you will record decisions and results during play.

8. Sequence of Play gives detailed step-by-step instructions for playing the game.

It is suggested that you read through components 1-7 first, then read through the "Sequence of Play" component while referencing the other components to get a general idea of how the game is played. Finally, follow the "Sequence of Play" to play the game.

Project Model

Project Description

The project to be constructed is a concrete girder river bridge, shown in profile in Figure 1. Two concrete abutments, each consisting of a front wall and two wing walls, as shown in Figure 9, are to be constructed one on each shore. Each abutment is to be set on a foundation of 25 steel H-piles. There will be four concrete piers in the river, the two inner piers being 20 feet higher than the two outer piers, as shown in Figure 10. Each pier is set on a foundation of 50 steel H-piles and a 10 feet by 26 feet by 36 feet pile cap, as shown in the same figure. The bridge superstructure consists of five spans, each containing 25 10 feet long precast concrete box girder segments. One segment of the superstructure is shown in Figure 11.

A critical path network for construction of either half of the

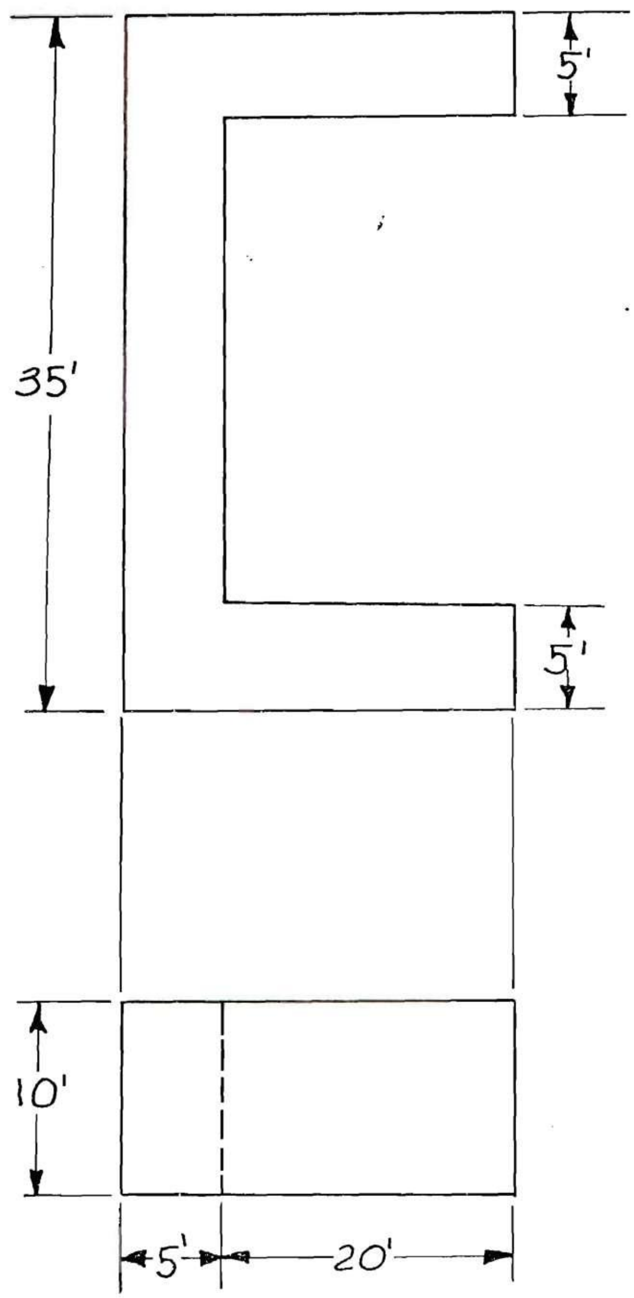

Figure 9. Abutment Dimensions

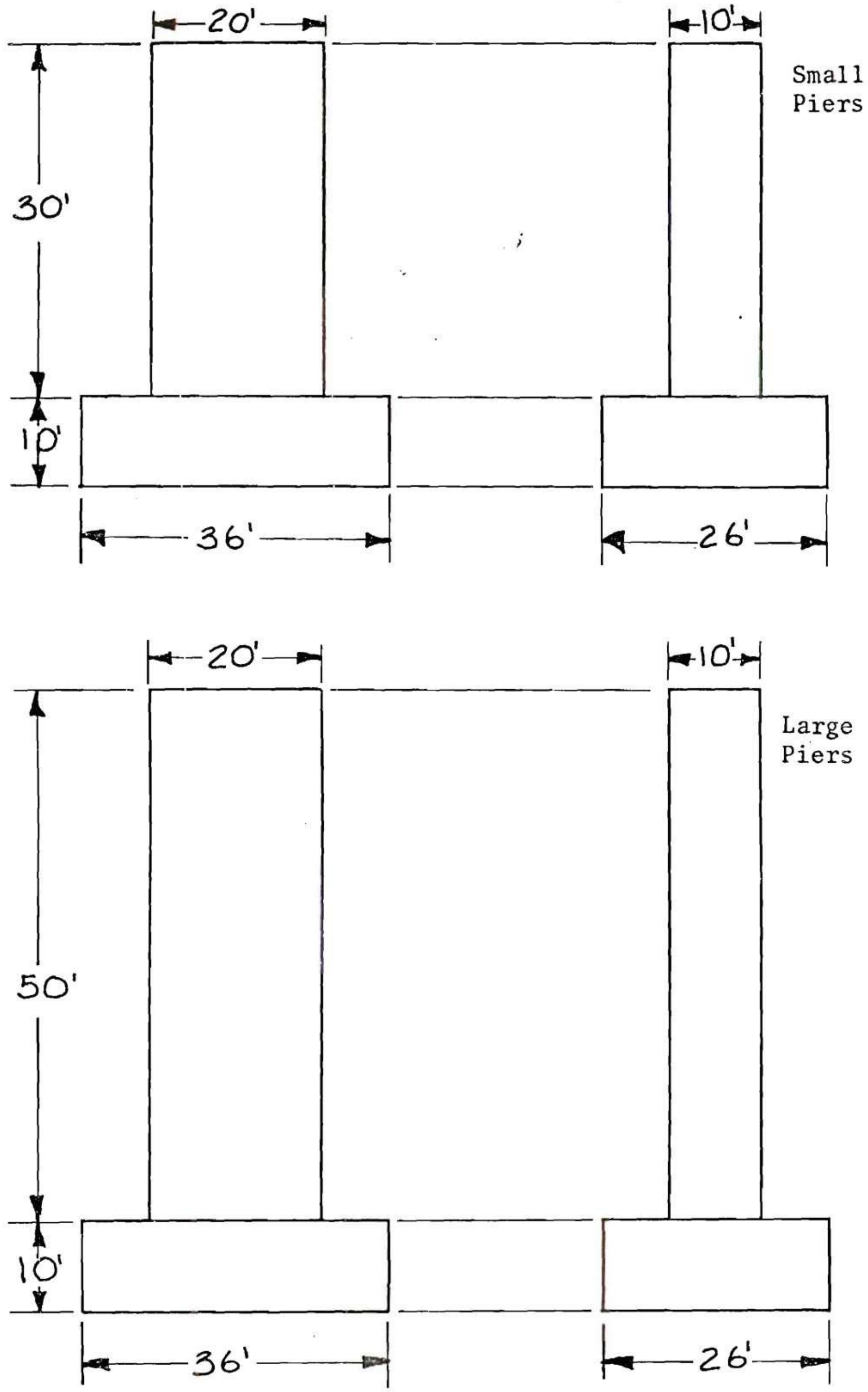

Figure 10. Pier Dimensions

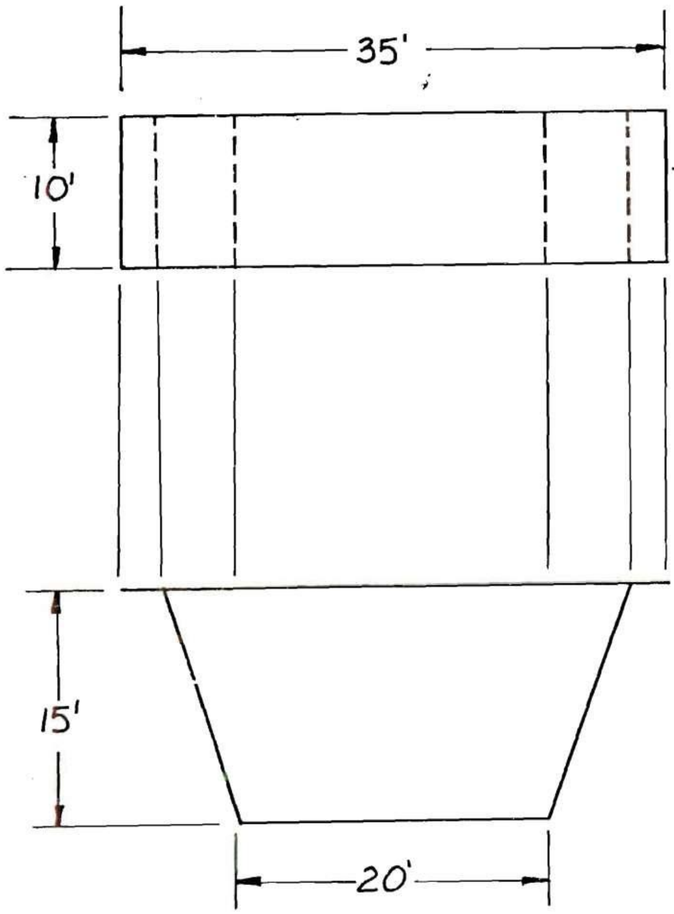

Figure 11. Concrete Box Girder for Superstructure

symmetrical bridge is shown in Figure 12. Construction is divided so that, if desired, work can proceed independently on all piers and abutments. Activities are given three-part numbers. The first number, "1" or "2," signifies one of the two symmetrical sides of the bridge. The letter following is either "A" for abutment activities, "L" for activities on a larger pier, or "S" for acticities on a smaller pier. The final number indicates the sequence of activities at any location. It is assumed that floating equipment must be used for river construction because barge traffic prohibits the use of falsework. Qualitative descriptions of the activities shown on Figure 6 to be performed on any pier, or either abutment, follow.

Pier Activities (1S, 1S, 2L, or 2S)

1. Set Frame for Cofferdam. A light frame of wood piles and wales is set and driven at the pier site to guide installation of a sheet pile cofferdam. A single floating crane with a hammer can carry and install this frame.

2. Drive Steel Sheet Pile Cofferdam. A steel sheet pile cofferdam is driven at the pier site to permit dewatering for pier construction. A barge delivers sheet piles to the site. A crane with a hammer sets and drives the sheeting. Work can be speeded by using a second crane to set and perhaps partially drive sheeting.

3. Excavation in Cofferdam. Earth in the cofferdam is excavated to the level of the bottom of the pile cap for the pier with a clamshell from a floating crane.

4. Drive H-Piles for Pier Foundation. H-piles are driven in the cofferdam before dewatering. They may be driven using followers,

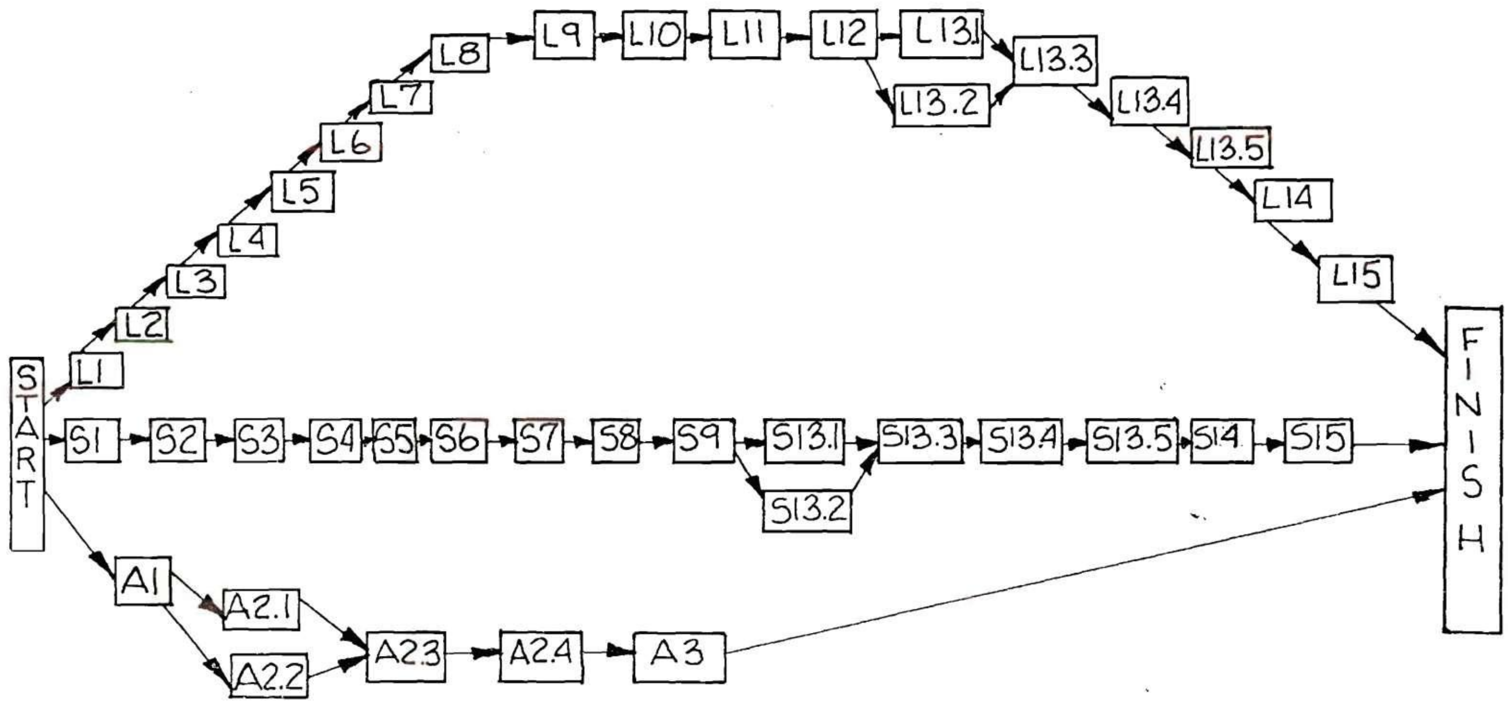

Figure 12. Project Network

or without followers if a hammer capable of underwater driving is used.

5. Set Reinforcing Steel for Pile Cap. The reinforcing steel cage for the pile cap is barged to the cofferdam and lowered into place by a floating crane.

6. Pour Pile Cap. The concrete pile cap is poured with a tremie pipe using the steel sheet pile cofferdam as forms. Concrete is delivered in concrete buckets on barges. A floating crane at the cofferdam lifts the buckets to the tremie chute for pouring.

7. Set Top Bracing Frame in Cofferdam. A steel beam bracing system is barged to the cofferdam and installed in it to enable it to withstand water pressures after dewatering. A floating crane handles the bracing at the cofferdam.

8. Pump Installation. Pumps are carried to the cofferdam on a barge, then installed on platforms beside the cofferdam, or lowered into the cofferdam if submersible, and all hoses and sumps rigged, to prepare for dewatering.

9. Dewatering of cofferdam. The cofferdam is pumped dry on smaller piers, or pumped five feet below the level of bracing on larger piers.

10. Lower Top Bracing Frame. On larger piers only, the initial bracing frame is lowered by crane to just above water level to allow a second frame to be installed at the top of the cofferdam, before dewatering is completed.

11. Install Second Bracing Frame. On larger piers only, the second bracing frame is barged to the cofferdam and installed by crane

at the top of the cofferdam in the position vacated by the lowered frame.

12. Complete Cofferdam Dewatering. On larger piers only, the cofferdam is completely dewatered after final bracing installation.

13. Pier Construction. Piers are cast in-situ. Lifts of 10, 20, 30, or 50 feet can be made. Reinforcing steel can be tied in place or tied on shore and then barged to the pier as a cage. Reusable metal forms are erected on shore, then barged to the pier site and set in place by crane. Concrete is delivered in concrete buckets on barges. A floating crane at the cofferdam lifts the buckets to the pier for pouring. Forms are stripped and cleaned to complete a cycle.

14. Extract Steel Sheet Pile Cofferdam. After pier construction is complete, sheet piles are pulled using a floating crane with an extractor.

15. Cantilever Construction of Precast Concrete Girder Superstructure. Precast concrete box girder sections 10 feet long are erected in balanced cantilever from both sides of a completed pier. Each box girder section is lifted from shore onto a barge by a floating crane. The two barges travel to the pier. The girder is then lifted up the previous erected section by the crane, attached by means of a simple steel beam carriage, and fully tensioned using hydraulic jacks.

Abutment Activities (1A or 2A)

1. Drive H-Piles for Abutment Foundation. H-piles are driven by a crane with a hammer.

2. Abutment Construction. Concrete abutment can be constructed in one operation, or front and wing walls can be constructed separately.

For any pour, reinforcing steel is tied and metal forms erected, then concrete is poured using a crane and bucket, and finally forms are stripped and cleaned.

3. Cantilever Erection of Precast Concrete Girder Superstructure. Precast concrete box girder sections are erected in cantilever from the abutment. Each box girder section is lifted to the previous erected section by a crane, attached by means of a simple steel beam carriage, and fully tensioned using hydraulic jacks.

For further information on cofferdam operations (1, 2, 3, 7, 8, 9, 10, 11, 12, 14) see White and Prentis,[20] Tomlinson,[21] Fang,[22] or How to Work with Sheet Piles.[23] For further information on pile driving (L or S4, A1) see Tomlinson[24] or Sowers.[25] For further information on in-situ concrete construction (L or S13, A2) see Paul,[26] or Western Construction.[27,28] For further information on cantilever erection of precast concrete box girders, see Libby,[29] O'Connor,[30] or ACI.[31]

Activity Information

General. The project requires a crane on shore (any size) at all times for loading barges, handling materials, deliveries, etc.

A "floating crane" in equipment requirements means a crane and a barge sufficient to carry the crane. The two units can be separated on previous and subsequent activities. A barge propulsion unit is not required unless specifically stated.

Pier Activities

1. Set Frame for Cofferdam

Amount of Work--total job

Equipment Requirements

a. Hammer--any on list

b. Hammer leads--20'

c. Floating crane--any on list

d. Barge propulsion unit--for floating crane

Time for Job--Eight hours

2. Drive Steel Sheet Pile Cofferdam

Amount of Work--see p. 67, cofferdam design for number of sheet piles

Three Alternate Methods:

Method 1: One crane with hammer sets and drives all sheeting

Equipment Requirements

a. Barge with propulsion unit--40 x 30

b. Hammer--any on list

c. Hammer leads 20'

d. Floating crane--to lift weight (sheet pile + hammer + leads) at height 120' (85' on smaller piers), radius 30'

e. Sheet piles--see p. 67, cofferdam design (charge until piles are extracted)

Time for Job

$$\text{hours for job} = \frac{\text{no. sheet piles}}{12} +$$

$$\frac{.4 \times 750{,}000}{(\text{ft lbs of hammer})(\text{blows/min or hammer})(\text{hammer effectiveness factor})} \times$$

$$\left(\frac{\text{no. sheet piles}}{10}\right)$$

see p. 67 for hammer effectiveness factor

Method 2: One crane sets sheeting, separate crane with hammer drives sheeting

Equipment Requirements

a. Barge with propulsion unit--50 x 30 (40 x 30 on smaller piers)

b. Floating crane--to set sheeting; to lift weight (sheet pile) at height 110' (85' on smaller pier), radius 30'

c. Hammer--any on list

d. Hammer leads--20'

e. Floating crane--to drive sheeting; to lift weight (hammer + leads) at height 45', radius 30'

Time for Job

$$\text{hours for job} = \left(\frac{\text{no. sheet piles}}{10}\right) \times$$

$$\frac{.4 \times 750{,}000}{(\text{ft lbs of hammer})(\text{blows/min of hammer})(\text{hammer effectiveness factor})}$$

see p. 67 for hammer effectiveness factor

Method 3: One crane with light hammer sets and tacks in sheeting, separate crane with larger hammer drives sheeting

Equipment Requirements

a. Barge with propulsion unit--50 x 30 (40 x 30 on smaller pier)

b. Light hammer--any on list

c. Light hammer leads--20'

d. Floating crane--to set and tack sheeting; to lift weight (sheet pile + light hammer + leads) at height 120' (85' on smaller piers), radius 30'

e. Larger hammer--any on list

f. Larger hammer leads--20'

g. Floating crane--to drive sheeting; to lift weight (larger hammer + leads) at height 45', radius 30'

Time for Job

$$\text{hours for job} = \left(\frac{\text{no. sheet piles}}{13.5}\right) \times \frac{.4 \times 750{,}000}{(\text{ft lbs of hammer})(\text{blows/min of hammer})(\text{hammer effectiveness factor})}$$

where all figures are for larger hammer; see p. 68 for hammer effectiveness factor.

3. Excavation in Cofferdam

Amount of Work--350 cy (525 cy on smaller piers)

Equipment Requirements

a. Clamshell bucket--any on list

b. Floating crane--to lift weight (bucket + volume of bucket x 145 pcf) at radius 25' (use duty cycle rating)

Time for Job

$$\text{hours for job} = \frac{\text{total cy}}{30 \times (\text{bucket factor})}$$

where bucket factor is .75 for 3/4 cy bucket, 1.0 for 1 cy bucket, 1.45 for 1 1/2 cy bucket, and 1.9 for 2 cy bucket

4. Drive H-Piles for Pier Foundation

Amount of Work--50 piles, each 55' long

Equipment Requirements

a. Barge with propulsion unit--40 x 30

b. Hammer--any on list

c. Hammer leads--70'

d. Floating crane--to lift weight (2915 lbs + hammer + leads) at height 20' (40' on smaller pier), radius 30'

Time for Job

$$\text{hours for job} = \frac{.5 \times 750{,}000 \times 40 \times (\text{follower factor})}{(\text{ft lbs of hammer})(\text{blows/min of hammer})(\text{hammer effectiveness factor})}$$

where follower factor = 1.2 if followers are used, 1.0 if hammer can drive underwater; see p. 67 for hammer effectiveness factor

5. Set Reinforcing Steel for Pile Cap

Amount of Work--total job

Equipment Requirements

a. Barge with propulsion unit--30 x 40

b. Floating crane--to lift 11 tons at radius 25'

Time for Job--four hours

6. Pour Pile Cap

Amount of Work--365 cy

Equipment Requirements

a. Concrete buckets--any number and size

b. Barges with propulsion units--30 x 40, any number

c. Floating crane--to lift weight (bucket + capacity × 150 pcf) at radius 10'

Time for Job--Each barge can carry up to four buckets of any size

$$\text{cy/hour from one barge} = \frac{60}{4 + 4\ (\text{no. buckets on barge})} \times (\text{total capacity of buckets on barge, cy})$$

cy/hour poured = sum of cy/hour from all barges (not to exceed 30 × largest bucket capacity)

$$\text{hours for job} = \frac{365}{\text{cy/hour poured}}$$

7. Set Top Bracing Frame in Cofferdam

Amount of Work--total job

Two Alternate Methods:

Method 1: Top frame in cofferdam is installed piecewise

Equipment Requirements

a. Barge with propulsion unit--40 x 30

b. Floating crane--any on list

Time for Job--16 hours

Method 2: Top frame in cofferdam is installed as a unit

Equipment Requirements

a. Barge with propulsion unit--40 x 30

b. Floating crane--to lift 8.77 tons at radius 25'

Time for Job--eight hours

8. Pump Installation

Amount of Work--number of pumps desired

Equipment Requirements

a. Pumps with hose--number and sizes desired

b. Barge with propulsion unit--40 x 30

c. Floating crane--any on list

Time for Job

	Number of Pumps			
	1	2	3	4 or more
hours on large cofferdam	3	5	6	8
hours on small cofferdam	3	4	6	6

9. Dewatering of Cofferdam

Amount of Work--175,000 gal (140,000 gal on smaller piers)

Equipment Requirements

a. Pumps with hose--number and sizes desired (do not exceed allowable suction heads)

Time for Job

	Friction head	Starting head*	Finish head*
large pier	15'	5'	25'
small pier	10'	5'	20'

*Suction head for centrifugal pumps. For each pump,

$$\text{gpm} = \frac{\text{gpm(starting+friction head)} + \text{gpm(finish+friction head)}}{2}$$

using correct suction heads to get figures

$$\text{hours for job} = \frac{\text{total gallons}}{(\text{sum of gpm for all pumps}) \times 60}$$

10. Lower Top Bracing Frame--Large Piers Only

Amount of Work--total job

Equipment Requirements

a. Floating crane--to life 8.77 tons at 25' radius

Time for Job--12 hours

11. Install Second Bracing Frame--Large Piers Only

Amount of Work--total job

Two Alternate Methods:

Method 1: Second frame is installed piecewise

Equipment Requirements

a. Barge with propulsion unit--40 x 30

b. Floating crane--any on list

Time for Job--12 hours

Method 2: Second frame is installed as a unit

Equipment Requirements

a. Barge with propulsion unit--40 x 30

b. Floating crane--to lift 8.77 tons at radius 25'

Time for Job--four hours

12. Complete Cofferdam Dewatering--Large Pier Only

Amount of Work--105,000 gal

Equipment Requirements

a. Submersible pumps with hose--number and sizes desired

Time for Job--friction head is 25', starting head is 25', finish head is 40'. Calculate gpm for each pump and hours for job as on activity (9) above.

13. Pier Construction--Each pier is constructed in lifts of 10', 20', 30', or 50'. Five subactivities are involved in each lift.

13.1. Tie Reinforcing Steel for Lift

Two Alternate Methods:

Method 1: Reinforcing steel cage is fabricated on shore

Equipment Requirements

a. Crane--any on list

Time for Job

lift	10'	20'	30'	50'
hours for job	14	27	40	68

Method 2: Reinforcing steel cage is fabricated in place

Equipment Requirements

a. Barge with propulsion unit--40 x 30

b. Floating crane--any on list

Time for Job

lift	10'	20'	30'	50'
hours for job	16	30	45	75

13.2 Erect Forms (Omit if forms from previous lift are being used)

Equipment Requirements

a. Crane--any on list (can be the same crane used for 13.1 if Method 2 is used on 13.1 and activities are concurrent)

b. Forms--see p. 67

Time for Job

lift	10'	20'	30'	50'
hours for job	4	8	11	18

13.3. Set Forms, Reinforcing Steel in Place

Equipment Requirements

a. Barge with propulsion unit--40 x 30

b. Floating crane--to lift weight as follows:

lift	10'	20'	30'	50'
weight (tons)	6	12	18	30

c. Forms--seep at radius 25'

Time for Job--one hour

13.4. Pour Concrete for Lift

Amount of Work

lift	10'	20'	30'	50'
cy	75	150	225	370

Equipment Requirements

a. Concrete buckets--any number and size

b. Barges with propulsion units--40 x 30, any number

c. Floating crane--to lift weight (bucket + capacity × 150 pcf) at radius 25'

d. Forms--seep, see p. 67

Time for Job--Calculate cy/hour poured as an activity (6) above

$$\text{hours for job} = \frac{\text{total cy}}{\text{cy/hour poured}}$$

13.5. Strip and Clean Forms

Equipment Requirements

a. Barge--30 x 40

b. Forms--see p. 67

c. Floating crane--to lift weight as follows:

lift	10'	20'	30'	50'
weight (tons)	6	12	18	30

Time for Job

lift	10'	20'	30'	50'
hours for job	2	4	5	8

14. Extract Steel Sheet Pile Cofferdam

Amount of Work--see p. 67, cofferdams, for number of sheet piles

Equipment Requirements

a. Extractor--any on list

b. Air compressor--for the extractor used

c. Barge with propulsion unit--40 x 30

d. Floating crane--to lift maximum tons pull of extractor at radius 10'

Time for Job

Extractor	400A	E2	E4
Sheet piles/hour	8	12	15

$$\text{hours for job} = \frac{\text{no. sheet piles}}{\text{sheet piles/hour}}$$

15. Cantilever Erection of Precast Concrete Girder Superstructure

Amount of Work--25 sections at each pier

Equipment Requirements

a. Barge with propulsion unit--40 x 30

b. Floating crane--to lift 60 tons at height 25', radius 20'

c. Barge propulsion unit--for the floating crane

d. Hydraulic jacks--four, each 100 tons

Time for Job--68 hours

Abutment Activities

1. Drive H-Piles for Abutment Foundation

Amount of Work--25 piles, each 55' long

Equipment Requirements

a. Hammer--any on list

b. Hammer leads--70'

c. Crane--to lift weight (2915 lbs + hammer + leads) at height 70', radius 10'

Time for Job

$$\text{hours for job} = \frac{750{,}000 \times 20}{(\text{ft lbs of hammer})(\text{blows/min of hammer})(\text{hammer effectiveness factor})}$$

see p. 67 for hammer effectiveness factor

2. Abutment Construction

Amount of Work

Front wall = 65 cy

Each wing wall = 28 cy

Total = 121 cy

Abutment can be constructed in one operation, or front and two wing walls can be constructed separately. Four sub-activities are involved in construction of any part.

2.1. Tie Reinforcing Steel

Equipment Requirements

a. Crane--any on list

Time for Job

	Total	Front Wall	Each Wing Wall
hours for job	22	12	5

2.2. Erect Abutment Forms

Equipment Requirements

a. Crane--any on list (can be the same crane used for 2.1 if activities are concurrent)

b. Forms--see p. 67

Time for Job	Total	Front Wall	Each Wing Wall
hours for job	9	5	2

2.3. Pour Concrete

Equipment Requirements

a. Concrete buckets--number and sizes desired

b. Crane--to lift weight (bucket + capacity × 150 pcf) at radius 10'

c. Forms--see p. 67

Time for Job

$$\text{hours for job} = \frac{\text{no. cy}}{30 \times \text{bucket capacity}}$$

2.4. Strip and Clean Forms

Equipment Requirements

a. Crane--any on list

Time for Job

	Total	Front Wall	Each Wing Wall
hours for job	3.5	2	1

3. Cantilever Erection of Recast Concrete Girder Superstructure

   Amount of Work--12 sections at each abutment

   Equipment Requirements

   a. Crane--to lift 60 tons at height 25', radius 20'

   b. Hydraulic jacks--two, each 100 tons

   Time for Job--33 hours

Miscellaneous Information

Sheet Piles for Cofferdams

Small Pier: Use 82 PZ27 sections and 4 CP41 sections, all 50' long. Weight of one sheet pile is 2025 lbs. Total weight of piling is 172,190 lbs.

Large Pier: Use 82 PZ27 sections and 4 CP41 sections, all 75' long. Weight of one sheet pile is 3037.5 lbs. Total weight of piling is 258,285 lbs.

Forms Required for Concreting Activities

Zee Rib Panels given in the equipment list are to be set with "length" dimension vertical and "width" dimension horizontal. Any combination of panels can be used to form an area as long as the proper orientation is maintained. For example, to form a 10 feet wide side of a pier for a 10 foot lift of pouring, possible combinations are two four feet wide panels with one two feet wide panel, all 10 feet long; or five two feet wide panels, all 10 feet long.

Hammer Effectiveness Factor

This factor accounts for the fact that as the ratio of the weight of a pile to the weight of the hammer ram increases, the percent of the energy of the ram that is actually used to drive the pile decreases and the percent of ram energy used up in rebound increases.[32] The table[33] below gives the hammer effectiveness factor for different values of W, the ratio of pile weight to hammer ram weight. In calculating W, pile weight should be taken as the weight of a single pile for H-piles, but as the weight of two sheet piles, which are normally driven in pairs.[34] (Weight of a 55' long H-pile such as used on this project is 2915 lbs. For weight of sheet piles see Sheet Piles for Cofferdams, p. 67.)

W	0	.25	.5	.75	1.0	1.25	1.5	1.75	2.0	2.25
HEF, %	100	83	70	60	52	47	43	40	37	34
W	2.5	2.75	3.0							
HEF, %	32	30	28							

Equipment Market

Units can be obtained by new purchase, rental, or used purchase.

Orders for new purchase or rental of machines can be filled after the waiting period shown in Table 1. Procurement decisions made before beginning play can be assumed to have been made during project planning so that they can be filled at any time after beginning. Procurement decisions subsequently made on the basis of results of play are subject to the full waiting periods.

The used equipment market is generated each month as follows:

Table 1. Equipment Availabilities

Type of Unit	Months Wait, New Purchase	Months Wait, Rental	No. Used Units per Month
Crane	6	6	2
Pump	0	0	2
Hammer, Extractor	6	6	5
Hammer leads	1	1	0
Air compressor	0	0	2
Clamshell or Concrete bucket	0	0	0
Hydraulic jack	0	0*	0
Barge	1	0*	0
Barge propulsion unit	1	0*	0
Sheet piling	1	1	0
Metal forms	1	1	0

*Not subject to rental

For each type of equipment, randomly select the number of units indicated in Table 1 from the list of available units.

For each unit selected, randomly select an age of from one year to the service life of the unit less one year. All units selected may be purchased used during that month.

The price for used equipment is (price new)(new service life - age)/(new service life).

Service life for used equipment is (new service life - age).

All purchased units must be retained until all work involving that type and size of unit is finished on the entire project, whether the unit involved is being utilized or not. Two units of each type may be removed without regard to the above requirement during the project.

Available units with prices and specifications follow.

Table 2. Available Cranes

Unit	Est. Service Life (yrs)	Rental Rate				Engine Type	Hp	Oil (gal)
		Price	Day	Week	Month			
17.5 ton	12	$52,000	$171	$511	$1559	Diesel	84	2.6
29 ton	12	$70,000	$256	$761	$2206	Diesel	93	2.8
40 ton	12	$79,000	$285	$841	$2688	Diesel	120	3.75
50 ton	12	$105,000	$315	$991	$2974	Diesel	116	3.6
65 ton	12	$140,000	$346	$1164	$3307	Diesel	172	5
90 ton	12	$280,000	$427	$1290	$3914	Diesel	289	9

Note: See Tables 3-9 and Figure 7 for crane ratings and working ranges.

Table 3. Maximum Rated Load in Pounds, 17.5-ton Crane

Boom Length, Ft	Radius, Ft				
	10	15	20	25	30
40	35,000	22,420	14,680	10,740	8,350
50	31,930	22,230	14,480	10,530	8,130
60		22,040	14,270	10,310	7,920
70		21,850	14,070	10,100	7,700
80			13,960	10,000	7,590

Table 4. Maximum Rated Load in Pounds, 29-ton Crane

Boom Length, Ft	Radius, Ft				
	10	15	20	25	30
40	58,000	30,820	20,430	15,070	11,800
50	50,370	30,740	20,330	14,970	11,690
60	38,220	30,670	20,240	14,820	11,600
70		30,570	20,130	14,750	11,470
80		27,670	20,030	14,640	11,350
90		23,170	19,910	14,510	11,220
100			19,800	14,390	11,090
110			18,330	14,260	10,960
120			17,030	14,140	10,830

Table 5. Maximum Rated Load in Pounds, 40-ton Crane

Boom Length, Ft	Radius, Ft				
	10	15	20	25	30
30	80,000	58,935	37,240	27,050	21,130
40	80,000	58,810	37,100	26,910	20,980
50		58,690	36,970	26,760	20,840
60		58,570	36,830	26,620	20,690
70			36,690	26,480	20,540
80			36,560	26,330	20,390
90			36,420	26,190	20,250
100				26,050	20,100
110				25,900	19,950
120				25,280	19,800

Table 6. Maximum Rated Load in Pounds, 50-ton Crane

Boom Length, Ft	Radius, Ft				
	10	15	20	25	30
40	100,000	80,050	51,190	37,350	29,230
50	100,000	80,020	51,110	37,270	29,110
60	90,030	80,000	51,040	37,160	29,010
70		79,920	50,920	37,020	28,850
80		65,100	50,790	36,870	28,700
90			50,650	36,710	28,530
100			50,520	36,560	28,380
110			46,840	36,400	28,200
120			40,850	36,230	28,020

Table 7. Maximum Rated Load in Pounds, 65-ton Crane

Boom Length, Ft	Radius, Ft				
	10	15	20	25	30
40	130,000	103,420	65,910	47,780	37,270
50		93,530	65,750	47,610	37,100
60		85,390	65,600	47,450	36,930
70			65,440	47,280	36,760
80			63,780	47,120	36,590
90			58,620	46,950	36,420
100				46,790	36,250
110				44,870	36,080
120				41,210	35,910

Table 8. Maximum Rated Load in Pounds, 90-ton Crane

Boom Length, Ft	Radius, Ft			
	15	20	25	30
60	180,000	14[illegible],060	106,340	82,270
70	180,000	148,970	106,190	82,090
80	176,980	148,850	106,020	81,890
90		148,690	105,810	81,650
100		137,490	105,620	81,440
110		119,330	105,390	81,180
120		111,720	105,150	80,910

Table 9. Clamshell Duty Cycle Rating for Cranes, Pounds, Radius 30'

Unit	Load
17.5 ton	6,520
29 ton	10,510
40 ton	11,000
50 ton	14,000
65 ton	16,000
90 ton	28,000

Table 10. Available Pumps

Unit	Est. Service Life (yrs)	Price	Rental Rate			Engine Type	Hp	Oil (gal)
			Day	Week	Month			
3" Centrifugal	6	$734	$13	$37	$106	Gas	10.5	1.5
4" Centrifugal	6	$3000	$20	$58	$170	Gas	21.5	2.8
6" Centrifugal	6	$4500	$33	$91	$269	Diesel	65	4
10" Centrifugal	6	$6430	$80	$243	$738	Diesel	87	14
2" Submersible	6	$600	$12	$37	$107	Gas	1.2	.25
3" Submersible	6	$900	$21	$62	$179	Gas	3	.5
Hose for 2"-4"		$110	$5	$11	$35			
Hose for 6"-10"		$1200	$15	$47	$148			

Note: Add cost of hose to cost of pumps for calculations. See Table 11 for pump performance data.

Table 11. Pump Performance Data

Suction Head, Ft	Total Head, Ft	Centrifugal				Submersible	
		3"	4"	6"	10"	2"	3"
5	15	400	600	1750	4400	95	350
5	20	400	600	1750	3800	80	330
20	30	240	340	1020	2900	65	295
25	40	170	290	700	1980	50	245
	50					10	180
	65					x	70

Table 12. Available Pile Hammers

Unit	Est Serv Life	Price	Rental Rate			Weight (lbs)	Rated Energy (F+lbs)	Blows/ min	Ram Wt. (lbs)	Rec. CFM
			Day	Week	Month					
DE-10 (diesel)	5	$13,000	$129	$387	$1,161	3,100	9,900	50	1,100	0
DE-20 (diesel)	5	$15,000	$188	$557	$1,357	5,375	18,800	50	2,000	0
DE-30 (diesel)	5	$18,200	$215	$640	$1,560	8,125	30,100	50	2,800	0
U 9B3 (Dbl-Acting)	5	$12,000	$ 96	$288	$ 745	7,000	8,750	145	1,600	900
U 10B3 (Dbl-Acting)	5	$15,000	$129	$384	$ 904	10,850	13,100	105	3,000	1200
U 11B3 (Dbl-Acting)	5	$18,000	$164	$490	$1,203	14,000	19,150	95	5,000	1200
No. 2 (Sngl-Acting)	5	$12,200	$ 64	$193	$ 504	6,700	7,260	70	3,000	450
No. 1 (Sngl-Acting)	5	$12,190	$ 79	$235	$ 620	15,000	15,000	60	5,000	1200
30C (Dbl-Acting)	5	$10,600	$ 89	$263	$ 631	7,036	7,260	133	3,000	600
50C (Dbl-Acting)	5	$14,840	$112	$327	$ 813	11,782	15,100	120	5,000	1200

Note: U-hammer can drive underwater, needs no followers.

Table 13. Available Pile Extractors

Unit	Est Serv Life	Price	Rental Rate			Weight (lbs)	Crane pull, tons	Ft lbs	Rec. CFM
			Day	Week	Month				
E2 (Extractor)	5	$6,000	$42	$180	$457	2,600	50	700	600
E4 (Extractor)	5	$8,430	$68	$258	$638	4,400	90	1,000	900
400A (Extractor)	5	$4,717	$65	$184	$459	2,850	50	500	450

Table 14. Hammer Leads

Unit	Est Serv Life	Price	Rental Rate			Weight (lbs)
			Day	Week	Month	
20' Hammer Leads	5	$1,000	$12	$30	$100	2,300
70' Hammer Leads	5	$4,000	$29	$87	$259	9,000

Table 15. Available Air Compressors

Unit	Est Serv Life	Price	Rental Rate			Engine Type	Hp	Oil (gal)
			Day	Week	Month			
250 cfm	5	$12,900	$49	$157	$459	Diesel	76	2.4
365 cfm	5	$19,0C0	$68	$208	$613	Diesel	109	3.4
600 cfm	5	$25,60J	$100	$305	$886	Diesel	167	5.2
900 cfm	5	$36,800	$147	$444	$1,300	Diesel	248	7.7
1,200 cfm	5	$49,700	$198	$601	$1,777	Diesel	328	10.2

Table 16. Concrete Buckets

Size (cy)	Est Serv Life	Price	Rental Rate: Day	Rental Rate: Week	Rental Rate: Month	Weight (lbs)
1/2	5	$425	$ 9	$ 23	$ 64	180
3/4	5	$475	$11	$ 30	$ 81	250
1	5	$525	$12	$ 34	$ 95	375
1 1/2	5	$675	$16	$ 45	$122	480
2	5	$950	$17	$ 53	$141	650

Table 17. Clamshell Buckets

Size (cy)	Est Serv Life	Price	Rental Rate: Day	Rental Rate: Week	Rental Rate: Month	Weight (lbs)
3/4	6	$3,300	$21	$ 63	$177	5,385
1	6	$4,285	$29	$ 79	$225	5,700
1 1/4	6	$4,560	$30	$ 84	$248	5,900
1 1/2	6	$6,110	$33	$101	$301	11,060
2	6	$6,470	$36	$123	$342	11,590

Table 18. Available Barge Sections

Section	Size	SL	Price
Standard	30 x 10	30	$5,850
Standard	40 x 10	30	$4,000
Standard	50 x 10	30	$7,750
Raked	30 x 10	30	$6,450
Raked	40 x 10	30	$7,800
Raked	50 x 10	30	$8,750

Table 19. Barge Section Arrangements

Dimensions	Max Crane (tons)	Sections Required
40 x 30	351	3: 40 x 10 or 4: 30 x 10*
50 x 30	50	3: 40 x 10 and 1: 30 x 10* or 5: 30 x 10*
60 x 30	60	3: 40 x 10 and 2: 30 x 10*
60 x 40	75	6: 40 x 10*
70 x 40	90	4: 50 x 10 and 2: 40 x 10*

*One section of this size should be raked for this arrangement.

Table 20. Price of Metal Concrete Forms

Panel Width Ft	Panel Length, Ft					
	1	2	4	8	10	12
1	$16.80	$33.60	$39.60	$70.40	$86.00	$100.80
1.5	21.60	43.20	52.80	92.40	112.50	131.40
2	24.00	48.00	64.00	105.60	128.00	148.80
2.5	30.00	60.00	80.00	132.00	160.00	186.00
3	36.00	72.00	96.00	158.40	192.00	223.20
3.5	42.00	84.00	102.20	168.00	203.00	235.20
4	48.00	96.00	116.80	192.00	232.00	268.80

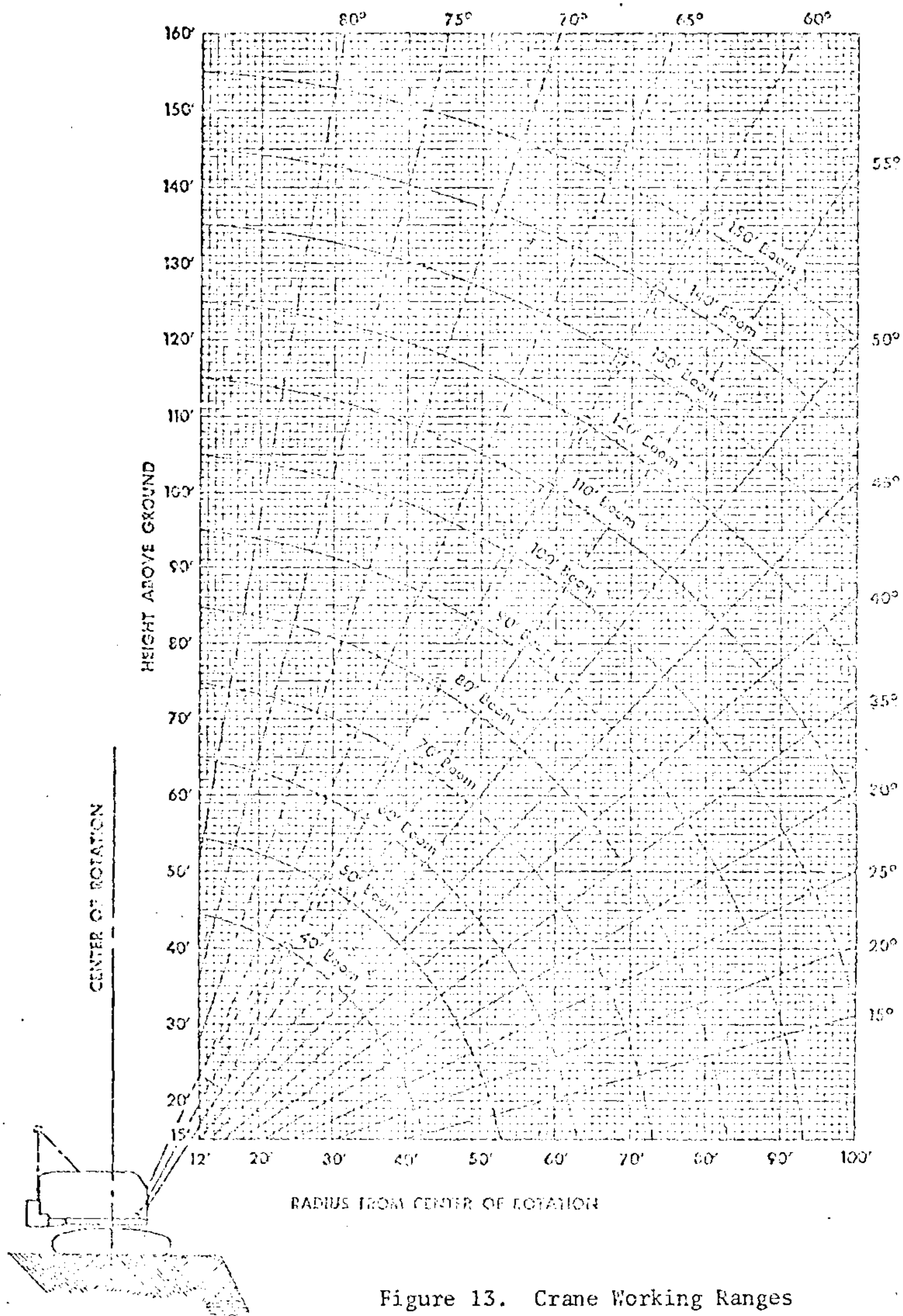

Figure 13. Crane Working Ranges

Barge Propulsion Unit with estimated service life 12 years, diesel engine with 218 ph and 6.8 gal oil, sells new for $15,000.

Hydraulic Jack, 100-ton capacity, with hand pump and hose, estimated service life five years, sells new for $786.

Steel Sheet Piling purchase at $230/ton and charge 50 percent of value to this job. Rent at $62/ton for first month and $6/ton for subsequent months.

Metal Concrete Forms purchase price from Table 20. Rent at 8.7 percent of purchase price per month. Charge 50 percent of value of purchased forms to this job.

Union Hall

See Table 21 for required operators and wage rates.

When there are five or more operating engineers on the job, a Master Mechanic must be in charge and receive not less than $.50 per hour above all other engineers on the job.

Engineers shall be paid for the full shift of work if any work is done on the shift.

Pay shall be one and one-half times the regular rate for all overtime work. (In the game, this is accomplished by paying for all hours at one and one-tenth the regular rate when the project is on overtime schedule.)

See "Sequence of Play," Appendix A, for application of the above provisions.

Table 21. Operators and Wage Rates per Hour

Unit	Operators	Base Wage	Health & Welfare	Pension	Apprentice	Total
(1) Crane, regardless of attachments	1 operator 1 oiler	$7.85 5.58	$.30 .30	$.15 .15	$.07 .07	$8.37 6.10
(2) Pump, 4" and under, up to 5; or over 4", one only	1 operator	4.91	.30	.15	.07	5.43
(3) Pump, over 4", up to four	1 operator	5.58	.30	.15	.07	6.10
(4) Air compressor, under 600 CFM	1 operator	4.91	.30	.15	.07	5.43
(5) Air compressor, 600 CFM and over	1 operator	6.13	.30	.15	.07	6.65
(6) Barge propulsion unit	1 operator	7.85	.30	.15	.07	8.37

Weather and Its Effects

Calculation of Weather Effects

To find daily weather: refer to the daily weather data, Table 23, for average daily temperature and wind speed and daily precipitation. Use average daily temperature and wind speed with Wind Chill Nomogram, Figure 8, to get the average daily wind chill equivalent temperature. In the nomogram, "the line for 4 mph is accented because this . . . is the generally accepted standard wind speed for calculating equivalent temperature."[35] To use the nomogram, "move horizontally to the left from the intersection of a given wind and temperature until the 4 mph line is reached. The vertical line intersected is the equivalent temperature."[36]

To find hours available during any week:

Base number of hours = 40 regular, or
50 overtime, or
80 double shift

For each day to be worked:

If wind chill temperature $\leq 0°$, subtract 8 hours regular, or
10 hours overtime, or
16 hours double shift

If a thunderstorm occurs, subtract

$$(1 - \text{rainfall factor}) \times \begin{cases} 8 \text{ hours regular, or} \\ 10 \text{ hours overtime, or} \\ 16 \text{ hours double shift} \end{cases}$$

where rainfall factor is given in Table 22.

Make all subtractions from base number of hours to find hours available.

To find effects of weather on activity durations: Calculate productivity factors for each day to be worked (not those completely omitted above) as follows:

Wind Chill Factor

If equivalent temperature > 60°, use 100%
If equivalent temperature is between 0° and 60°, use
(((eq. temp.)/60)(75) + 25)%
If equivalent temperature < 0°, use 0%

Rainfall Factor

Use rainfall factors from Table 22, only for precipitation other than thunderstorms.

Temperature Factor (only for activities L or S 2,4,6,9,12,13.4, 13.5,14 or A2.3)

Temperature > 32° use 100%
Temperature $\leq$ 32° use 0%

Wind Factor (only for activities L or S 2,14,15 or A3)

If wind speed < 10 mph, use 100%
If wind speed is between 10 mph and 20 mph, use
((20 - wind speed in mph)(5) + 50)%
If wind speed > 20 mph, use 0%

Average productivity factors of each type for the days of the week to find productivity factors for the week. Productivity on a given activity during the week is the product of the applicable productivity factors for that week.

Then for each activity,

weather expanded duration = (base duration)/(productivity)

Example Calculations

For 2 January 1972, temperature of 47° and wind speed of 9.4 mph gives wind chill temperature of 40°. Precipitation is .53", heavy fog. No hours are lost from this day. Factors are as follows:

Wind chill factor = (40/60)(75) + 25 = 75%
Rainfall factor = 90%

Temperature factor = 100%
Wind factor = 100%

If these calculations are performed for 1-5 January, 1972, the average of all values for each factor are:

Wind chill factor = 67.5%
Rainfall factor = 87.6%
Temperature factor = 100%
Wind factor = 93.7%

If, for example, activity L1 were worked during this week, its duration would be divided by (67.5%)(87.6%), or 59.1%.

If, for example, activity L2 were worked during this week, its duration would be divided by (67.5%)(87.6%)(93.7%), or 55.4%.

Table 22. Rainfall Factors

Rainfall, In.	Rainfall Factor, %	Rainfall, In	Rainfall Factor, %
0 to .1	100	.8 to .9	72
.1 to .2	98	.9 to 1	66
.2 to .3	96	1 to 1.1	60
.3 to .4	94	1.1 to 1.2	48
.4 to .5	92	1.2 to 1.3	36
.5 to .6	90	1.3 to 1.4	24
.6 to .7	84	1.4 to 1.5	12
.7 to .8	78	1.5 and over	0

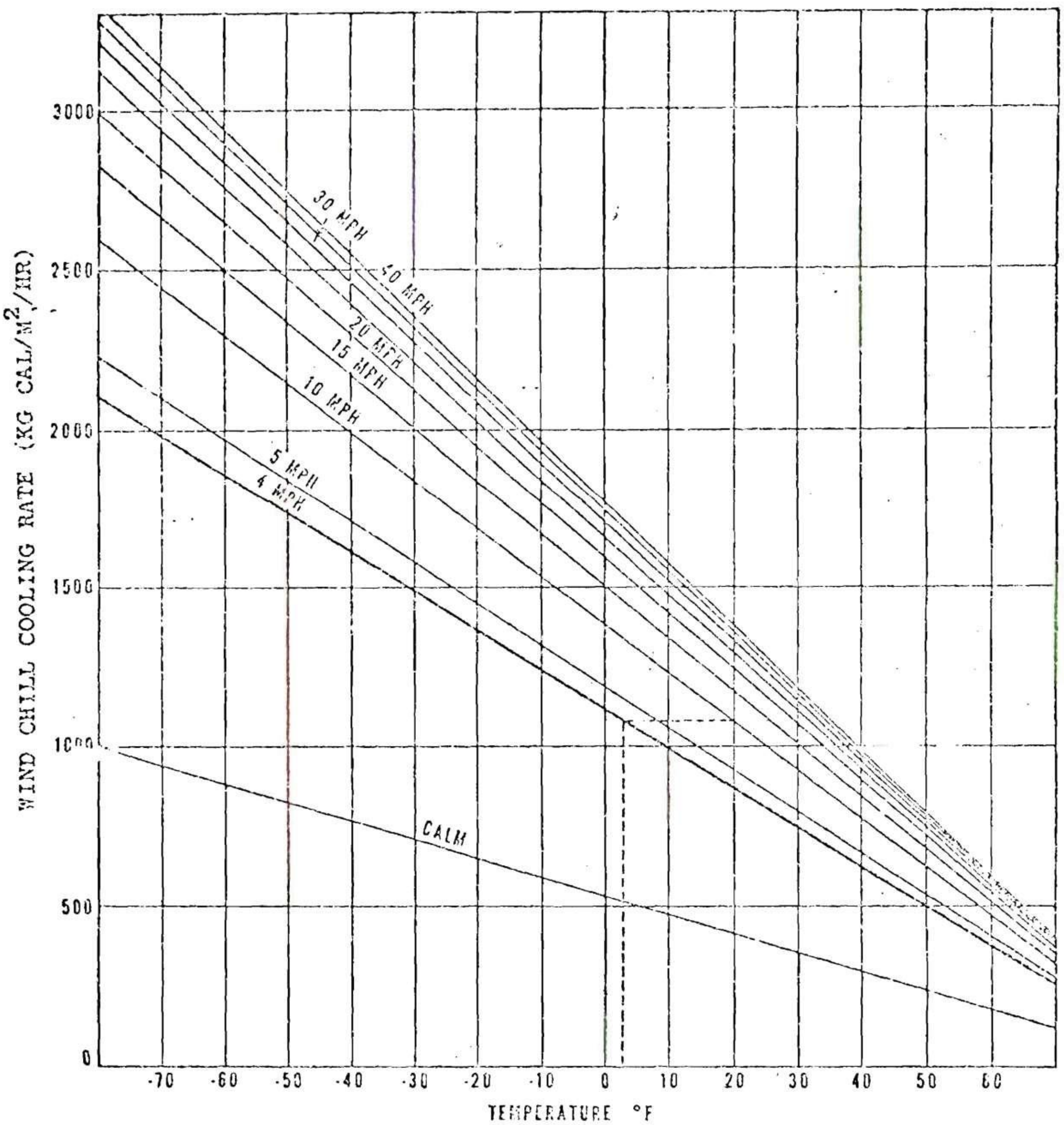

Figure 14. Wind Chill Index Nomogram

Table 23. Daily Weather Data

Date	Average Temp, °F	Precipitation, in	Average Wind Speed, mph
1972 January			
1	48	T	11.7
2	47	.53	9.4
3	41	T	10.5
4	51	1.11	9.5
5	42	.02	14.1
6	35	0	7.9
7	38	0	10.5
8	41	0	11.7
9	50	1.75*	8.9
10	60	1.94*	10.1
11	56	.88*	6.9
12	54	0	6.9
13	65	.52*	11.2
14	49	.01	14.2
15	24	0	17.8
16	17	0	9.6
17	29	0	7.2
18	42	0	6.0
19	52	0	5.9
20	53	.08	5.3
21	58	.02	5.3
22	55	.18	6.6
23	58	T	8.5
24	61	.01	8.3
25	49	.07	15.1
26	46	0	8.2
27	56	0	5.0
28	54	.08	10.4
29	47	1.82	5.2
30	41	.24	10.1
31	37	0	10.4
1972 February			
1	38	.18	13.5
2	38	.06	9.8
3	36	.74	14.7
4	29	0	16.4
5	33	0	7.8
6	38	.46	7.5
7	39	.05	13.8
8	35	0	7.6

Table 23. Continued

Date	Average Temp, °F	Precipitation, in	Average Wind Speed, mph
		1972 February	
9	42	0	5.9
10	40	0	9.6
11	44	0	9.6
12	41	.77	11.4
13	40	T	15.5
14	46	0	9.2
15	46	T	5.9
16	45	.21*	11.5
17	45	.21	8.1
18	40	.18	11.2
19	33	T	22.1
20	40	0	15.0
21	42	T	7.6
22	52	T	11.1
23	40	T	10.8
24	52	T	9.1
25	63	0	8.1
26	53	.30*	13.2
27	40	0	10.5
28	52	0	7.1
29	60	0	8.8
		1972 March	
1	61	.56*	11.7
2	61	.86*	12.1
3	43	T	11.8
4	45	.06	7.8
5	44	.06	12.8
6	40	0	7.3
7	50	0	8.8
8	48	.52*	15.2
9	42	0	9.5
10	49	0	8.6
11	54	0	7.9
12	58	0	6.2
13	61	.02	11.2
14	59	.09	11.1
15	58	0	8.9
16	56	1.00	12.1
17	48	.01	12.7
18	43	.12	6.6
19	55	0	5.5

Table 23. Continued

Date	Average Temp, °F	Precipitation, in	Average Wind Speed, mph
1972 March			
20	60	0	5.3
21	64	.11*	12.8
22	58	.10*	17.1
23	54	0	17.0
24	45	0	10.6
25	42	.16	9.6
26	46	0	8.3
27	57	.01	8.5
28	68	.13*	7.9
29	65	.43*	9.1
30	52	.02	11.2
31	45	.23	11.4
1972 April			
1	49	T	8.8
2	45	0	10.6
3	56	.42*	9.2
4	53	.17	11.9
5	53	0	8.3
6	62	0	7.9
7	66	.73*	14.2
8	49	.05*	15.0
9	47	0	10.6
10	53	0	5.9
11	59	.01	9.2
12	71	.01	11.8
13	74	0	13.7
14	74	0	11.8
15	75	0	12.5
16	72	T	17.3
17	65	0	13.5
18	66	0	7.9
19	67	0	7.3
20	70	0	9.4
21	68	T	10.9
22	62	.92	11.2
23	66	0	6.9
24	63	0	10.2
25	55	0	13.2
26	54	0	7.8

Table 23. Continued

Date	Average Temp, °F	Precipitation, in	Average Wind Speed, mph
		1972 April	
27	59	0	4.5
28	60	0	7.8
29	65	T	9.2
30	67	0	9.6
		1972 May	
1	68	0	8.2
2	70	T*	8.3
3	64	.40*	7.1
4	61	0	10.8
5	63	0	7.5
6	66	0	8.6
7	66	T	10.2
8	69	.69	13.5
9	65	T	15.4
10	61	0	9.1
11	62	0	12.5
12	64	T	12.8
13	62	2.05	13.8
14	70	.06	7.3
15	70	.18	9.4
16	67	0	8.1
17	65	T	8.1
18	69	T	8.9
19	65	.03	10.5
20	64	.05	7.6
21	65	.02	8.5
22	69	.23*	9.4
23	69	.24*	9.2
24	70	T*	6.0
25	73	.03*	5.6
26	69	0	12.5
27	67	0	14.2
28	63	.01	13.2
29	71	T	9.9
30	73	.29*	7.5
31	66	0	12.7

Table 23. Continued

Date	Average Temp, °F	Precipitation, in	Average Wind Speed, mph
1972 June			
1	61	0	10.8
2	64	0	4.0
3	69	0	3.0
4	72	0	4.0
5	78	0	8.8
6	78	.09*	9.5
7	76	T	8.1
8	75	0	7.1
9	76	0	10.2
10	77	0	9.9
11	69	0	15.1
12	68	0	8.8
13	73	0	6.5
14	75	0	7.5
15	76	0	7.3
16	75	0	6.5
17	76	T	8.9
18	75	.11	12.2
19	69	1.42	20.3
20	69	1.81	18.0
21	75	0	16.7
22	67	0	14.0
23	67	0	12.2
24	69	0	10.8
25	74	T	7.6
26	74	T	9.8
27	71	.61*	9.5
28	74	T*	8.3
29	76	0	10.9
30	74	0	8.3
1972 July			
1	74	0	8.2
2	76	0	8.6
3	79	0	9.1
4	78	.45*	11.8
5	71	.02	10.1
6	70	T	7.8
7	71	0	6.2
8	74	0	4.0
9	73	0	4.2

Table 23. Continued

Date	Average Temp, °F	Precipitation, in	Average Wind Speed, mph
		1972 July	
10	73	0	8.6
11	77	0	9.5
12	78	0	7.3
13	79	.02*	6.5
14	76	0	8.1
15	77	.47*	7.8
16	76	0	7.1
17	76	.29*	4.6
18	78	T*	5.6
19	78	.05	4.3
20	77	0	7.5
21	80	0	3.7
22	83	T*	4.8
23	84	.28*	6.2
24	82	0	7.2
25	80	0*	9.2
26	79	T*	8.2
27	79	.09*	11.5
28	78	.42*	7.8
29	76	.11*	10.8
30	77	.17	9.4
31	76	1.44*	4.9
		1972 August	
1	78	0	7.3
2	78	T	7.2
3	79	T	7.3
4	80	T	8.5
5	79	.65*	8.8
6	78	0	6.3
7	81	0*	9.5
8	79	0	7.8
9	80	.46*	7.9
10	76	.12*	7.9
11	75	.05*	7.5
12	76	0	6.6
13	77	.27*	4.9
14	76	0	5.3
15	77	.30	4.2
16	76	0	8.8

Table 23. Continued

Date	Average Temp, °F	Precipitation, in	Average Wind Speed, mph
		1972 August	
17	76	T	6.0
18	80	0	10.5
19	81	0	9.1
20	80	.89*	7.5
21	76	0	8.5
22	75	0	6.0
23	78	0	7.6
24	78	0*	5.9
25	78	T*	4.2
26	80	T*	3.6
27	79	0	5.0
28	75	0	8.5
29	76	T	6.8
30	78	0	8.5
31	76	0	10.9
		1972 September	
1	75	0	6.6
2	75	0	4.8
3	76	0	5.2
4	78	.03*	5.2
5	71	.47	7.5
6	71	T	8.3
7	72	0	4.8
8	72	0	4.5
9	79	0	9.5
10	74	0	12.2
11	70	0	8.5
12	72	0	4.3
13	74	0	4.9
14	78	0	8.2
15	81	.04*	7.8
16	79	0	6.6
17	76	.31*	5.3
18	73	.36	5.3
19	78	0	7.3
20	77	0	10.2
21	70	0	8.2
22	75	0	4.3
23	76	0	7.6

Table 23. Continued

Date	Average Temp, °F	Precipitation, in	Average Wind Speed, mph
		1972 September	
24	74	0	9.6
25	74	T	9.5
26	79	.08	6.8
27	78	0	6.5
28	76	0	4.6
29	79	.02*	7.8
30	62	.55*	11.9
		1972 October	
1	56	0	8.9
2	61	0	10.8
3	64	0	13.1
4	68	T	11.5
5	67	.35	8.3
6	65	0	10.8
7	65	0	11.5
8	60	0	9.6
9	64	0	6.3
10	64	0	15.4
11	62	0	12.4
12	66	0	7.6
13	70	.05	7.6
14	68	.25	5.9
15	69	0	7.9
16	66	0	4.9
17	70	0	8.6
18	64	0	10.2
19	52	.02	10.5
20	45	0	14.8
21	48	0	12.1
22	60	0	10.5
23	66	.28	7.9
24	60	0	8.8
25	53	0	10.6
26	54	T	8.9
27	55	2.08	15.5
28	57	.01	8.2
29	60	0	8.9
30	62	T	9.5
31	63	0	10.2

Table 23. Continued

Date	Average Temp, °F	Precipitation, in	Average Wind Speed, mph
	1972 November		
1	61	T	6.8
2	70	.05	8.8
3	67	.46	6.3
4	60	0	9.1
5	55	0	9.2
6	55	T	14.5
7	53	.68	11.1
8	53	0	12.1
9	53	0	6.3
10	57	T	7.2
11	55	0	8.8
12	58	0	7.8
13	56	.72*	12.5
14	54	.02	11.9
15	47	0	11.4
16	41	0	9.8
17	42	0	6.2
18	42	T	9.1
19	51	.89	10.8
20	42	0	10.8
21	44	T	6.9
22	42	T	9.9
23	38	0	8.2
24	39	0	5.2
25	39	.80	9.1
26	40	T	13.2
27	45	0	9.5
28	49	.05	11.7
29	44	0	11.7
30	40	.29	9.1
	1972 December		
1	40	0	7.9
2	45	0	4.6
3	47	0	4.2
4	53	T	6.2
5	61	.25	7.6
6	53	.16	9.8
7	45	0	11.8
8	45	T	12.1

Table 23. Continued

Date	Average Temp, °F	Precipitation, in	Average Wind Speed, mph
		1972 December	
9	56	.01	7.1
10	64	.27	9.6
11	52	.02	6.9
12	52	T	11.1
13	53	.11	5.2
14	59	2.11*	5.6
15	45	1.14	14.1
16	30	0	15.2
17	28	0	10.9
18	35	0	3.7
19	44	.01	6.0
20	56	.84	7.6
21	58	1.49	7.9
22	52	T	10.5
23	50	T	6.9
24	46	T	8.2
25	49	0	10.4
26	38	.02	10.8
27	39	0	11.2
28	47	0	8.2
29	50	0	8.2
30	54	0	11.2
31	58	1.19	9.9
		1973 January	
1	53	T	9.2
2	47	.02	7.9
3	44	.29	14.5
4	49	.11	7.9
5	44	1.40	7.9
6	41	.18	8.6
7	35	3.48	8.6
8	29	.43	10.5
9	29	T	9.1
10	28	T	8.3
11	30	0	10.8
12	27	0	9.5
13	28	0	3.6
14	37	0	7.2
15	44	0	10.1

Table 23. Continued

Date	Average Temp, °F	Precipitation, in	Average Wind Speed, mph
	1973 January		
16	42	0	6.8
17	48	0	5.0
18	55	.07*	9.5
19	50	.62*	10.9
20	50	0	8.3
21	50	1.45	15.7
22	53	T	12.9
23	49	0	9.9
24	44	0	10.5
25	45	0	5.8
26	49	.64	10.6
27	43	0	8.3
28	44	.20	12.2
29	31	T	16.3
30	32	0	6.0
31	40	0	4.8
	1973 February		
1			13.4
2			11.1
3			14.8
4			9.6
5			7.3
6			7.1
7			5.2
8			12.7
9			14.1
10			12.9
11			5.9
12			9.1
13			10.9
14			10.1
15			15.0
16			18.6
17			8.5
18			7.5
19			5.2
20			11.2
21			12.2
22			12.8
23			10.5

Table 23. Continued

Date	Average Tem , °F	Precipitation, in	Average Wind Speed, mph
	1973 February		
24	51	0	7.5
25	49	T	7.8
26	56	T	4.2
27	52	0	10.1
28	45	0	8.8
	1973 March		
1	49	0	8.5
2	51	.17	10.9
3	64	T	8.2
4	61	.42*	7.9
5	63	0	6.5
6	64	.42*	12.4
7	63	T*	11.5
8	65	T	8.5
9	62	.62	11.8
10	62	T	12.5
11	63	1.10*	10.9
12	64	0	9.1
13	63	0	6.2
14	69	0	10.6
15	72	0	14.0
16	63	2.57*	17.8
17	44	T	19.3
18	46	0	13.2
19	55	0	7.3
20	53	.93	8.1
21	48	T	14.4
22	47	0	9.4
23	52	0	6.9
24	56	T	13.5
25	57	.75	15.2
26	53	.01	14.1
27	55	0	8.6
28	58	0	10.6
29	52	.16	14.4
30	51	.15	11.9
31	61	2.23*	12.2

Table 23. Continued

Date	Average Temp, °F	Precipitation, in	Average Wind Speed, mph
1973 April			
1	64	0	13.5
2	58	0	11.9
3	58	.01	10.5
4	52	.02	14.2
5	49	0	11.7
6	50	0	6.0
7	50	2.38	11.7
8	54	T	9.9
9	52	T	11.8
10	43	0	17.5
11	41	0	11.5
12	53	T	13.1
13	53	0	10.9
14	54	0	7.1
15	58	0	10.6
16	60	T	10.9
17	63	.02	10.2
18	65	T	14.2
19	68	.05	11.4
20	69	0	10.1
21	68	0	9.4
22	67	0	9.5
23	66	0	9.6
24	67	.61*	6.8
25	64	.29	8.5
26	63	.65*	7.3
27	54	T	16.7
28	52	0	11.5
29	57	0	5.8
30	63	0	7.6
1973 May			
1	65	0	8.6
2	65	T	9.1
3	62	.32	11.5
4	56	0	11.2
5	58	0	7.3
6	58	0	6.0
7	64	T	10.4
8	68	.75	12.7

Table 23. Continued

Date	Average Temp, °F	Precipitation, in	Average Wind Speed, mph
		1973 May	
9	68	T	10.2
10	70	0	8.6
11	72	.07*	11.7
12	66	.27*	9.6
13	62	0	8.9
14	62	0	8.5
15	59	0	12.5
16	55	0	9.8
17	61	T	10.6
18	55	0	6.2
19	56	1.32*	8.6
20	65	1.27*	9.4
21	67	0	8.5
22	69	0	6.6
23	74	.62*	12.7
24	68	.31*	14.4
25	68	.01*	6.8
26	70	0	6.5
27	73	.10*	14.7
28	75	2.10*	12.5
29	71	0	8.3
30	70	0	9.1
31	69	0	6.9
		1973 June	
1	71	.25	5.5
2	74	0	5.5
3	76	0	5.8
4	74	0	7.8
5	77	.20*	9.8
6	72	.24	8.6
7	73	0	6.0
8	74	.16*	10.4
9	72	.41	9.4
10	76	.06	7.8
11	77	0	7.1
12	77	T*	7.1
13	75	0	7.5
14	77	0	7.2
15	78	.08*	4.3

Table 23. Continued

Date	Average Temp, °F	Precipitation, in	Average Wind Speed, mph
		1973 June	
16	79	T*	5.9
17	79	.04*	8.8
18	79	0	7.6
19	78	T*	7.5
20	77	1.41*	6.6
21	78	T	6.2
22	76	0	8.6
23	76	0	8.9
24	74	0	6.2
25	76	T*	5.0
26	74	0	5.0
27	76	T	5.5
28	78	.50*	11.9
29	73	0	9.6
30	76	T	4.0
		1973 July	
1	81	0	6.6
2	81	0	6.2
3	80	T	5.8
4	82	0*	7.9
5	78	T	9.1
6	78	0	5.6
7	78	.10*	3.7
8	80	.25*	7.8
9	80	.19*	7.8
10	80	.09*	7.5
11	77	T	8.6
12	79	0	10.9
13	78	0	8.5
14	80	.18	6.9
15	80	T	9.9
16	79	.24*	8.1
17	77	.18*	5.0
18	72	.29*	10.6
19	78	0	9.6
20	79	0	7.6
21	79	0	4.6
22	81	0*	5.5
23	82	T*	7.6
24	78	T	8.6

Table 23. Continued

Date	Average Temp, °F	Precipitation, in	Average Wind Speed, mph
	1973 July		
25	78	T*	8.5
26	78	.58*	5.9
27	79	0	7.8
28	80	0	7.2
29	81	0	8.9
30	79	T	5.9
31	81	0	5.5
	1973 August		
1	79	.06*	6.5
2	77	T	6.2
3	77	0	7.2
4	75	0	6.0
5	77	0	4.8
6	78	.15*	5.8
7	77	0	6.8
8	77	T	7.1
9	79	0	4.9
10	80	0*	5.6
11	80	0*	5.6
12	79	.50*	7.5
13	79	T*	8.6
14	78	.43*	9.5
15	76	T	5.5
16	77	0	6.5
17	78	T	4.8
18	77	.11	4.8
19	76	0	5.2
20	78	T*	8.5
21	75	0	12.2
22	73	0	9.9
23	73	0	10.5
24	75	0	8.8
25	76	0	7.5
26	77	0	8.8
27	80	0	6.0
28	81	0	5.2
29	79	0	4.6
30	80	0*	5.9
31	80	.10	9.9

Table 23. Continued

Date	Average Temp, °F	Precipitation, in	Average Wind Speed, mph
		1973 September	
1	80	0	12.7
2	77	T	9.9
3	79	0	7.5
4	78	0	8.1
5	77	0	9.1
6	79	0	6.9
7	79	0	5.2
8	80	0	3.7
9	81	.58*	6.3
10	80	0	8.3
11	78	0	7.8
12	77	0	5.6
13	75	.68*	9.8
14	78	.02	13.2
15	75	0	7.5
16	76	.06	7.8
17	75	.71*	8.1
18	66	0	8.8
19	64	0	7.2
20	71	0	4.5
21	73	0	6.5
22	77	T	7.8
23	76	0	4.5
24	77	0	7.1
25	75	0	13.4
26	72	.11	19.1
27	74	.84	10.9
28	74	.13	6.9
29	75	T	6.6
30	74	1.03*	4.8
		1973 October	
1	68	.45	8.5
2	70	T	4.9
3	72	0	4.2
4	74	0	1.9
5	75	0	8.1
6	72	0	11.1
7	69	0	7.9
8	71	0	5.3

Table 23. Continued

Date	Average Temp, °F	Precipitation, in	Average Wind Speed, mph
		1973 October	
9	71	0	8.3
10	71	0	6.6
11	70	0	10.8
12	66	0	10.4
13	68	0	8.3
14	68	.01	7.9
15	67	0	5.2
16	65	0	8.5
17	58	0	9.1
18	58	0	7.1
19	61	0	7.5
20	64	0	5.9
21	66	0	8.9
22	65	0	9.9
23	65	0	5.6
24	62	0	3.7
25	65	0	7.6
26	66	0	9.1
27	65	0	5.3
28	55	.14	10.4
29	43	T	12.4
30	48	0	11.5
31	50	.15	8.6
		1973 November	
1	54	0	8.5
2	59	0	5.8
3	66	0	7.2
4	68	0	6.5
5	58	T	13.8
6	48	0	6.5
7	48	.02	5.3
8	58	.03	6.6
9	50	.19	14.7
10	40	0	8.5
11	41	0	8.6
12	46	0	2.9
13	52	0	5.6
14	58	0	8.9
15	62	.14	10.2

Table 23. Continued

Date	Average Temp, °F	Precipitation, in	Average Wind Speed, mph
		1973 November	
16	52	T	12.5
17	48	0	8.6
18	51	0	6.6
19	58	0	3.2
20	57	.02	11.7
21	58	1.38	9.1
22	61	T	5.5
23	62	0	4.9
24	63	0	5.8
25	68	.07	11.7
26	70	.09	11.9
27	73	.11	14.4
28	54	.26	16.5
29	43	0	12.8
30	49	0	8.6
		1973 December	
1	55	0	8.1
2	53	0	9.9
3	56	0	9.4
4	59	.55	14.1
5	50	1.20*	11.1
6	44	0	9.6
7	38	0	8.5
8	38	T	10.5
9	43	0	10.8
10	36	T	14.0
11	31	0	10.5
12	41	0	7.8
13	58	T	17.5
14	47	0	9.4
15	43	.91*	9.4
16	36	0	18.4
17	30	T	17.4
18	36	0	6.3
19	35	0	16.0
20	38	.69	14.1
21	28	T	19.0
22	30	0	7.6
23	42	0	4.0

Table 23. Continued

Date	Average Temp, °F	Precipitation, in	Average Wind Speed, mph
	1973 December		
24	47	0	10.8
25	50	.03	14.7
26	58	1.35	12.2
27	49	0	8.6
28	43	0	6.6
29	49	.87*	9.9
30	51	.09	9.1
31	62	2.42*	12.8

*Thunderstorm T = An amount too small to measure

Cost and Breakdowns

For each unit acquired, calculate and record the following information on a card.

1. Crane, Hammer, Extractor, Pump, Air Compressor, Barge Propulsion Unit

Purchased New

Service life, hours per year from Table 24.

C_o = price from "Equipment Market" component (p. 57).

Ownership cost per week = depreciation per week (Table 25)
+ 11T and Storage per week (Table 49).

Operating cost per hour = fuel + oil + maintenance (Table 30).

Initial % downtime from Table 27.

P_1, P_2 for breakdowns from Table 28.

Repair cost per hour for breakdowns from Table 29.

Operator(s)' wages per hour from "Union Hall' component (p. 74)

Purchased Used

Service life, hours per year when new from Table 24.

Age from "Equipment Market."

Used service life = (service life when new) - (age).

C_o = (price from Equipment Market)(used service life)/(service life when new)

Ownership cost per week = depreciation per week (Table 26)
+ 11T and Storage per week (Table 49)

Final five entries same as for "Purchased New."

Rented

Age, generated with a random number using uniform distribution over the equipment's service life.

Ownership cost per week = rental rate from "Equipment Market."

Operating cost, Initial % downtime, P_1 and P_2, Operators as for "Purchased New."

2. Hammer Leads, Barge, Clamshell or Concrete Bucket

Service life, hours per year from Table 24.

C_o = price from "Equipment Market."

Ownership cost per week = depreciation per week (Table 25) + 11T and Storage per week (Table 49).

No operating costs.

No operators.

No breakdowns.

3. Sheet Piling and Metal Forms

Purchased New

Charge 50% of cost to this job.

Rented

Use rental rate from "Equipment Market."

No operating costs.

No operators.

No breakdowns.

Example: New 17.5-ton crane with average maintenance

Service life = 12 years   Hours per year = 1600

C_o = \$52,000

Ownership cost per week = (.3208/100)\$52,000

+ (.1249/100)\$52,000 = \$231.76

Operating cost per hour = \$.887 + \$.103 + \$.294 = \$1.28

Initial % downtime: Random Number (from a table) = 5738 so use 6%

$P_2 = .1081 \times 6 \div 800 = .0008$

$P_1 = .0081$

Repair cost per hour = (.1461/100)\$52,000 ÷ 6(% down)

= \$12.66.

Table 24. Service Life and Hours per Year

Unit	Service Life, years	Hours per Year
Crane, 17.5-ton	12	1600
Crane, other	12	1400
Hammer, Extractor	5	1400
Hammer Leads	5	1400
Barge	30	1400
Pump	6	1200
Concrete Bucket	5	1200
Clamshell Bucket	6	1200
Air Compressor	5	1200
Barge Propulsion Unit	12	1400
Hydraulic Jack	5	1200

Table 25. Depreciation per Week, DDB, % of C_o

Service Life, years	Present Year of Service Life				
	1	2	3	4	5
5	.7693	.3074	.1228	.0491	.0197
6	.6409	.2134	.0709	.0239	.0077
12	.3208	.0533	.0091	.0014	.0002
30	.1285				

Table 26. Depreciation per Week, DB, % of C_o

Present Year of Service Life	Service Life, Years									
	1	2	3	4	5	6	7	8	9	10
1	1.9226	.9616	.6409	.4808	.3847	.3208	.2745	.2401	.2134	.1923
2		.4808	.2134	.1200	.0772	.0533	.0393	.0302	.0213	.0190

Table 27. Initial Percent Downtime Generation

Mainte-nance	Initial Percent Downtime							
	9	1	3	4	5	6	7	8
Bad	8125-9999	0000-0625	0625-1250	1250-1875	1875-2500	2500-4375	4375-6250	6250-8125
Average	8750-9999	0000-1250	1250-2500	2500-3750	3750-5000	5000-6750	6750-7500	7500-8750
Good	9375-9999	0000-1875	1875-3750	3750-5625	5625-7500	7500-8125	8125-8750	8750-9375

Draw a Random Number and take initial percent downtime from the range the RN falls in, using assigned type of maintenance.

Table 28. Breakdown Probability, 800 P_2/(Initial % down)

Maintenance	Present Year of Service Life											
	1	2	3	4	5	6	7	8	9	10	11	12
Average	.1081	.1189	.1308	.1439	.1553	.1741	.1915	.2107	.2317	.2549	.2804	.3084
Bad	.1081	.1243	.1430	.1644	.1891	.2174	.2501	.2876	.3307	.3803	.4373	.5030
Good	.1081	.1135	.1192	.1251	.1341	.1380	.1449	.1522	.1597	.1677	.1761	.1841

Assume maintenance you are using and use year of <u>original</u> service life for used and rented units.

P_2 = (entry in Table) × (initial % down)/800 $P_1 = 10\ P_2$

Table 29. Repair Rate × (Initial % down), % of C_o

Service Life, years	Expected Hours per Year	Rep. Rate (In. % down)
5	1200	.6820
5	1400	.5850
6	1200	.5401
12	1400	.1670
12	1600	.1461

Use new C_o for used equipment.

Table 30. Operating Costs

Unit	Fuel/ Hr	Oil/Hr			Maint & Minor Repairs/Hr		
		Good Maint	Avg Maint	Bad Maint	Good Maint	Avg Maint	Bad Maint
17.5-ton Crane	$ .887	$.119	$.103	$.096	$.588	$.294	$.147
29-ton Crane	.983	.130	.114	.105	.651	.325	.163
40-ton Crane	1.268	.170	.148	.137	.840	.420	.210
50-ton Crane	1.226	.164	.143	.132	.812	.406	.203
65-ton Crane	1.817	.238	.208	.193	1.204	.602	.301
90-ton Crane	3.053	.410	.357	.330	2.022	1.011	.506
3" Centr. Pump	.018	.016	.014	.012	.105	.052	.026
4" Centr. Pump	.037	.031	.027	.025	.215	.107	.054
6" Centr. Pump	.687	.074	.068	.065	.456	.228	.114
10" Centr. Pump	.919	.137	.118	.106	.609	.304	.152
2" Submers. Pump	.002	.002	.002	.002	.012	.006	.003
3" Submers. Pump	.005	.005	.004	.004	.030	.015	.008
250 CFM Air Comp.	.803	.108	.094	.087	.532	.266	.133
365 CFM Air Comp.	1.152	.155	.135	.124	.763	.381	.191
600 CFM Air Comp.	1.764	.237	.206	.191	1.169	.584	.292
900 CFM Air Comp.	2.620	.351	.306	.283	1.736	.868	.434
1200 CFM Air Comp.	3.465	.465	.405	.374	2.296	1.148	.574
Barge Propulsion Unit	2.303	.309	.269	.249	1.526	.763	.381
DE-10 Pile Hammer	.237	.037	.031	.028	--	--	--
DE-20 Pile Hammer	.423	.088	.070	.061	--	--	--
DE-30 Pile Hammer	.528	.132	.102	.088	--	--	--

Table 49. Interest, Insurance, Taxes, and Storage per Week, % of C_o

Service Life, Years											
1	2	3	4	5	6	7	8	9	10	11	12
.2309	.1734	.1537	.1439	.1383	.1341	.1320	.1299	.1277	.1270	.1256	.1249

Weekly Networks

The game is played in periods. Each period represents a calendar week on an actual project. During each period of play, a weekly network is developed incorporating logical relationships between all activities which will be worked during the period. These networks are in "circle" or "Precedence" notation.* The nature of such a weekly network can best be explained by example. As an example, assume that the player has decided to schedule activities 1L1, 1L2, 1S1, and 1S2 from the Project Model during a given week.

The basic weekly network is obtained by taking that portion of the Project Critical Path Network which contains the activities scheduled for the period. The Project Critical Path Network is given in the Project Model. For the example, the basic weekly network appears as in Figure 15a.

The basic weekly network is refined by adding constraints representing equipment requirements for the period. For example, activities 1L1, 1L2, and 1S1 all require the use of a floating crane with a hammer. Suppose the same floating crane with hammer is assigned to all three activities, with the plan of working 1S1 after 1L1 and 1L2. Then an additional constraint arrow is needed on the weekly network, showing that 1S1 cannot begin until 1L2 is finished. This is shown in Figure 15b. Similar constraints should be included for all activities of the period which will require the same equipment units.

The important parameter calculated from a weekly network in the

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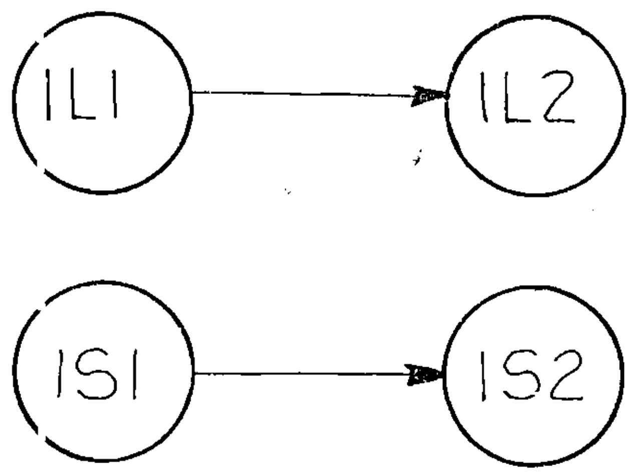
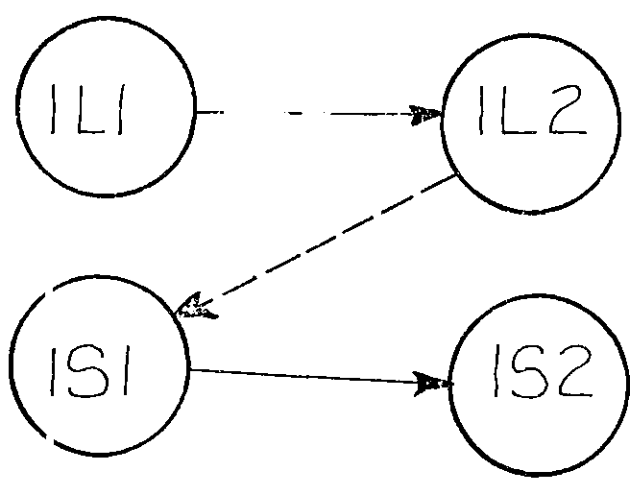
*If unfamiliar with Critical Path Networks, see Antill and Woodhead in Bibliography.



(a)



(b)

Figure 15. Example of Weekly Network

game is an early start time (EST) for each activity. This parameter is calculated based on various activity durations to generate various results for the period. Whatever activity durations are used, the EST of any activity j is given by:

EST of j = maximum (EST of i + duration of i) where i is any activity immediately preceding j in the network. EST for initial activities in the period is the starting time of the period, expressed in working hours from the start of the project. For the example, assume the period is the first of the project, so EST of the initial activity 1L1 is 0. If durations for activities 1L1, 1L2, and 1S1 are 8.2, 12.3, and 10.2 hours, respectively, then the EST values for 1L2, 1S1, and 1S2, are 8.2, 20.5, and 30.7, respectively.

Forms

Form A

This form, with sample entries, appears as follows:

Unit Purchased	Price	Age (years)	First Week	Last Week
1. 90 ton Crane	$280,000	New	1	12
2. DE-30 Hammer	18,300	New	1	3

This form is used to record equipment purchases and sales for the entire project. Each time a unit of equipment is purchased from the Equipment Market, it is recorded along with its price and age. "First Week" is the first week that the unit is purchased for the project. "Last Week" is the last week that the unit is retained on the project. Entries should be numbered consecutively "1, 2, 3, . . ." so that every purchased unit has a unique number.

Form B

This form, with sample entries, appears as follows:

	Unit Rented	First Week	Last Week
R1)	2 yd clamshell bucket	1	2
R2)	7" centrifugal pump	3	5

This form is used to record equipment rentals for the entire project. Each time a unit of equipment is rented from the Equipment Market, it is recorded. "First Week" is the first week that the unit is rented for the project. "Last Week" is the last week that the unit is retained on the project. Entries should be numbered consecutively "R1, R2, R3, . . ." so that every rented unit has a unique number.

Form C

This form, with sample entries appears as shown on the following page. It is used to record costs incurred during any period of play. A new form should be used for each period. For each period, all equipment procured and still retained, as listed on Forms A and B, should be listed on Form C. "Hours Worked" are taken from Form D for the period. Repair times and cost entries are generated during play and recorded. If a Master Mechanic is employed during the week, this is also recorded on Form C, as shown on the following page.

Form D

This form, with sample entries, appears as shown on the following page. It is used to record equipment assignments and work completed during any period. A new form should be used for each period. All activities to be worked during the period are listed under the heading "Activity." Equipment assigned to each activity is listed under "Units

Form C

Machine	Hours Worked	Hours Field Repair	Hours Shop Repair	Ownership Rental Cost	Operating Cost	Operator's Wages	Repair Cost	Total Cost
1) 90-ton Crane	29.8	0	0	$1248	$163	$431	0	$1842
2) DE-30 Hammer	19.9	9	0	166	13	0	241	420
R2) 6" centrifugal pump	2.8	0	0	33	3	15	0	51
Master Mechanic	40							354

Form D

Activity	Regular Hours	Units Used	Weather Productivity	Breakdown Delays	Percent Complete	Finish Time
1L1	8.2	3,6,8,14,1	.98	7	100	8.2
1S2	2.3	1,6,8,10,12,14, R1,R3,5,11	.98	0	31	

Used," using the numbers assigned to equipment on Forms A and B. During play for the period, "Regular Hours" worked, "Weather Productivity," "Breakdown Delays," and "Percent Complete" will be calculated and recorded for each activity. "Finish Time," which is also calculated and recorded during play for each activity, is given in working hours from the start of the project.

Sequence of Play

This section provides step-by-step instructions for playing the game. There are two parts to this section. The instructions in Part I, "Project Planning," should be followed at the start of the game. Thereafter, the game is played by periods. Each period represents a calendar week on an actual project. The instructions in Part II, "Play for a Period," should be followed for every period in the game.

I. Project Planning

Follow these steps at the start of the game.

1. Determine the starting date and time limit for the project. If these have not been assigned to you, you may choose a time limit of from 10 to 20 weeks, and a starting date from 1 January 1972 to a date that will allow completion by 31 December 1973.
2. Plan the entire project. Utilize the following information in planning:
   a. All information in the "Project Model." On an actual project, this type of information would come from a market estimate.

b. All information in the "Equipment Market" and "Union Hall." On an actual project, type of information would be obtained from unions or equipment dealers.

c. All information in the "Cost and Breakdowns" tables. On an actual project, such information could be estimated with good accuracy.

d. General information from "Weather and Its Effects" to get some idea of how weather will affect work on your project. It is undesirable to closely examine the weather data during planning, since no actual project manager knows exactly what weather will occur.

The object in planning is to find a way to complete the project within the time limit at lowest possible cost. Specific decisions that can further this object include:

a. Type, size, and number of equipment units to use on the project.

b. Most advantageous financial basis for procurement of all equipment, rental or purchase.

c. Sequence of working on activities and assigning equipment to activities to permit maximum utilization of equipment and completion of the project within the time limit.

For useful equipment planning information, see Antill and Woodhead, Clough, Peurifoy, or Day (in Bibliography).

3. Decide on all advance purchase and rental orders, in accordance with your plan. (See Equipment Market, p. 68. Note that orders made now can be filled at any time after play

begins, while later orders will be subject to waiting periods.) Record all orders on Form A or B (see Forms, p. 120).

4. Decide whether to use good, average, or poor maintenance. This decision holds for the entire project. As the level of maintenance increases, operating costs increase while time and cost of breakdowns decrease.

II. Play for a Period

After planning, the project proceeds in successive periods, each period representing a calendar week. For each period, the instructions below should be followed. There are six steps, each including several instructions. Figure 5 shows the function of each step in the interaction of components and player decisions that generates results.

In step one, as shown in Figure 5, you will generate weekly decisions for the period based on your Project Plan, the results from previous periods that indicate how the plan is progressing, and information in the "Project Model," "Equipment Market," and "Union Hall." In step two, you will translate your weekly decisions into a basic weekly network using information in the "Project Model." In step three, as Figure 5 shows, the basic weekly network and information in the "Weather and Its Effects" component are used to produce a weather expanded network. In step four, the weather expanded network and the "Cost and Breakdowns" component are used to produce a final weekly network. In step five, work progress for the period is calculated from the final weekly network. Finally, in step six, costs for the period are calculated from the final weekly network and the "Cost and

Breakdowns" component.

A complete form of Part II of the Sequence of Play is given below. A summary of Part II in tabular form follows the complete form. This summary can be used after you have become familiar with the game to avoid reading through the detailed form for every period.

Step 1. Initial Decisions

1. Activity scheduling

   a. Decide what activities will be worked this week, based on your plan and results from previous periods. List all these scheduled activities on Form D for the week (see Forms, p. 120).

   b. Extract those portions of the Project Network which contain scheduled activities to produce a weekly network (see Weekly Networks, p. 118).

2. Equipment Procurement

   a. Make all purchases, sales, or rentals desired and possible according to Equipment Market (see p. 68) and your previously placed orders on Forms A and B. Record purchases and sales on Form A, rentals on Form B (see Forms, p. 120).

   b. Calculate and record each new unit's cost and breakdown information on a card (see Cost and Breakdowns, p. 110).

3. Equipment Assignments

   a. Assign procured equipment, as listed on Forms A and B, to scheduled activities based on activity equipment requirements (see Activity Information, p. 54). No activity can be worked without a complete set of required equipment. Record equipment assignments on Form D (see Forms, p. 120).

b. On the weekly network, draw equipment constraints for activities which will use the same units (see Weekly Networks, p. 118).

4. Employ a Master Mechanic for the week if necessary (see Union Hall, p. 84) and record on Form C (see Forms, p. 120).

5. Select the basis for this week's work:

   Regular time: Five days, eight hours per day, 40 hours total

   Overtime: Five days, ten hours per day, 50 hours total

   Double time: Five days, 16 hours per day, 80 hours total

Step 2. Basic Weekly Network

For each activity scheduled for the period, as listed on Form D, follow 1-2 below:

1. Calculate "Time for Job" for the activity given the assigned equipment, using Activity Information, p. 54).

2. Multiply "Time for Job" by (100% - latest previous percent complete on Form D for previous period) to get basic duration for this activity this week. Record this basic duration on the weekly network drawn in Step 1.

Step 3. Weather Expanded Weekly Network

1. Find weather for this week (see Table 23, Daily Weather Data).

2. Calculate Hours Available this week from base time available and weather effects (see Calculation of Weather Effects,

p. 86). Record Hours Available this week on weekly network.

3. Calculate weather productivity factor for this week for each scheduled activity (see Calculation of Weather Effects) and record on Form D.

4. Expand each activity's basic duration from Step 2 by the appropriate productivity factor to produce weather expanded activity durations (see Calculation of Weather Effects). Record weather expanded activity durations on weekly network in place of basic durations from Step 2.

Step 4. Final Weekly Network

1. Calculate early start time (EST) of all scheduled activities using the weather expanded network from Step 3 (see Weekly Networks, p. 118).

2. Select the activity with earliest EST. If two or more activities share the earliest EST, select one randomly.

3. Calculate hours worked for the selected activity using EST from the previous step as follows:

   a. If (EST + weather expanded duration) $\leq$ Hours Available this week, then hours worked = weather expanded duration.

   b. If (EST + weather expanded duration) $\leq$ Hours Available this week, then hours worked = (Hours Available this week - EST).

4. For every unit of equipment assigned to the selected activity, as listed on Form D for the week, check for a breakdown as follows:

a. Find p_1, p_2 as recorded on a card when the unit was first procured.

b. Calculate (p_1 x hours worked) and (($p_1 + p_2$) x hours worked).

c. Draw a random number (use random number table or other method).

d. If $0 \leq$ random number $\leq$ (p_1 x hours worked), then a small breakdown occurs, of duration two to eight hours, randomly chosen.

e. If (p_1 x hours worked) $\leq$ random number $\leq$ (($p_1 + p_2$) x hours worked), then large breakdown occurs, of duration two to four days, randomly chosen, or of duration one day for rented units. Each day represents eight regular hours, or 10 overtime hours, or 16 double time hours.

5. For every breakdown that occurs on the selected activity, do the following:

   a. Find Repair cost rate for broken unit as recorded on a card when the unit was first procured.

   b. Calculate breakdown cost as (breakdown duration x Repair cost rate). [Note: No breakdown costs are charged for rented units.]

   c. Record duration and cost of breakdown on Form C for the week. Large breakdowns are recorded as "Shop Repair," small breakdowns as "Field Repair."

   d. Determine the effect of the breakdown on the weekly network. Three options are available:

i) No remedies are made.

(a) Increase the duration of the activity on which the breakdown occurred by the duration of the breakdown.

(b) Record the new activity duration in place of the weather expanded duration on the weekly network.

(c) Record the breakdown delay on Form D.

ii) An equivalent unit of equipment may be shifted from a concurrent activity to replace the broken unit during repair:

(a) Increase the duration of the concurrent activity by the duration of the breakdown.

(b) Record that new duration on the weekly network.

(c) Record the work performed by the shifted unit of equipment during repair on Form C for the week.

(d) Record the breakdown delay on the concurrent activity on Form D.

iii) An equivalent unit of equipment that was not assigned during the breakdown may replace the broken unit during repair. Record the work performed by this unit during repair on Form C for the week.

6. Recalculate EST of all activities using the weekly network

revised for breakdowns that have occurred.

7. Select the activity with earliest EST that has not been checked for breakdowns. Repeat 3-6 for this activity. Stop when all activities scheduled for the week have been checked.

Step 5. Work Progress for the Period

1. Separate completed and uncompleted activities for the week using the final weekly network, as follows:
   a. If (EST + final duration) $\leq$ Hours Available this week, the activity is completed this week.
   b. If (EST + final duration) < Hours Available this week, the activity is uncompleted this week.
2. For completed activities, calculate and record on Form D:
   a. Hours worked - final duration (from final weekly network) - breakdown delays (from Form D).
   b. Percent complete = 100%.
3. For uncompleted activities, calculate and record on Form D:
   a. Hours worked = Hours Available this week (from final weekly network) - EST (from final weekly network) - breakdown delays (from Form D).
   b. Percent complete = (Hours Available this week - EST - breakdown delays) x (100 - latest previous percent complete on Form D for previous weeks)/(final duration - breakdown delays) + latest previous percent complete.

Step 6. Costs for the Period

For <u>every</u> unit of equipment on the project during the week, as listed on Forms A and B, calculate the following information and record on Form C for the period:

1. Hours worked = sum of hours worked for all activities the unit was assigned to (as shown on Form D for the period).
2. Ownership/Rental cost.
    a. For purchased units, use ownership cost per week (as recorded on a card).
    b. For rented units, use (rental charge per period) x (whole number of periods worked + one for any fraction of a period worked), where for rental purposes 1 day = 8 hours, 1 week = 40 hours, 1 month = 176 hours.
3. Operating Cost = hours worked x operating cost per hour (as recorded on a card).
4. Operator's wages.
    a. For regular and double time weeks, use (hours worked + hours field repair) x wage rate as recorded on a card.
    b. For overtime weeks, use 1.1 x (hours worked + hours field repair) x wage rate as recorded on a card.

Summary of Play for a Period

Reference		Action	Record on
		Step 1. Initial Decisions	
Plan; Previous Results	1a.	Schedule weekly activities	Form D
Weekly Networks*	1b.	Draw weekly network	
Equipment Market*; Previous Orders	2a.	Procure equipment	Forms A & B
Cost and Breakdowns*	2b.	Calculate cost and breakdown information for new units	cards
Activity Information*; Forms A,B,D	3a.	Assign equipment to activities	Form D
Weekly Networks*	3b.	Add equipment constraints to weekly network	
Union Hall*	4.	Employ Master Mechanic	Form C
	5.	Select basis for work: regular, double, or overtime	
		Step 2. Basic Weekly Network	
Form D		For each activity scheduled:	
Activity Information*	1.	Calculate Time for Job	
1) above; Previous Form D's	2.	Calculate Base Time for this week	Weekly Network
		Step 3. Weather Expanded Weekly Network	
Table 23	1.	Find weekly weather	
1) above; Weather and Its Effects*	2.	Calculate Hours Available this week	Weekly Network

Reference		Action	Record on
1) above; Weather and Its Effects*	3.	Calculate weather productivity factors	Form D
Weekly network; 3) above	4.	Calculate weather expanded activity durations	Weekly network
		Step 4. Final Weekly Network	
Weekly network	1.	Calculate EST of all activities	
1) above	2.	Select activity w/minimum EST	
Weekly network	3.	Calculate hours worked for the selected activity	
Form D; cards of equipment information	4.	Check each unit assigned to selected activity for breakdown a. If RN $\leq p_1$ x hours, small breakdown, 2-8 hours b. If p_1 x hours $\leq$ RN $\leq (p_1 + p_2)$ x hours, large breakdown, 2-4 days	
4) above	5.	For any breakdown on selected activity:	
cards of equipment information	a-c.	Calculate breakdown duration and cost	Form C
	d.	Determine effect of breakdown on weekly network	
		i) No remedies--increase duration of selected activity	Form D; Weekly network
		ii) Unit shifted from concurrent activity--increase duration of concurrent activity	Form D; Weekly network Form C
		iii) Idle unit used	Form C
Weekly network	6.	Recalculate EST of all activities	

Reference	Action	Record on
6) above	7. Select activity with minimum EST that has not been checked and repeat 3-7.	
	Step 5. Work Progress for the Period	
Weekly network	1. Separate completed and uncompleted activities	
Weekly network	2. Calculate Hours Worked, % Complete for completed activities	Form D
Weekly network; Previous Form D's	3. Calculate Hours Worked, % Complete = (Hours Available - EST - Breakdown Delays)(100% - Previous % Complete)/(Weather expanded duration) + (Previous % Complete) for uncompleted activities	Form D
	Step 6 Costs for the Period	
Forms A,B,C; Cards of equipment information	For all units, calculate cost information	Form C

APPENDIX B

AN EXAMPLE OF PLAY

Introduction

This chapter presents an example of play of the game. A preliminary estimate is given to provide a basis for comparison of results of play. The plan for construction decided on before the game is given. The decisions and results of play for each period are discussed generally. Procedure of play for one week is examined in detail.

The descriptions of plans, decisions, and results for the example are necessarily somewhat detailed. The reader should refer to the "Project Model" component of the game, Appendix A, p. 46, to clarify any references to project activities.

Preliminary Estimate

A preliminary estimate of durations and costs is made before beginning play to provide a basis for comparison of results of play. This was necessary because the game had not been played before. In the first part of the preliminary estimate, estimated activity durations and a time limit for the project are calculated. In the second part of the preliminary estimate, a figure for the project cost is calculated. A time limit of 12 weeks and an estimated cost of $149,006 are the results of these calculations. The procedure followed is not recommended for generating preliminary estimates for the game in all cases. It is felt that results of actual games will provide a better basis for comparison in the future.

A preliminary estimate of durations and costs is made before beginning play to provide a basis for comparison of results of play.

The first part of the preliminary estimate is determination of estimated activity durations and a time limit for the project. For all activities, methods and equipment are assumed in the estimate that will result in low cost rates and long durations, so that some compression from the estimated solution will be available. For example, in activities L and S7, bracing frames for cofferdams are assumed to be installed piecewise, which would take longer than installation as a unit but permit a much smaller crane to be used. Base times for activities can be computed from assumed equipment assignments using Activity Information in Appendix A. Using these base times, the longest chain through the project network is about eight weeks. A time limit of 12 weeks is established to allow for some shifting of activities. The period of October through December 1973 is chosen as the time for simulated construction. Average weather productivity factors for that period are computed from the monthly average temperature, rainfall, and wind speed using the procedures explained in Calculation of Weather Effects in Appendix A. Base times for activities are then expanded by these weather factors to produce estimated activity durations. The time limit determined in this part of the preliminary estimate is imposed for the subsequent play. The estimated durations will be used in planning before play, as explained below.

The second part of the preliminary estimate is determination of an estimated project cost. Cost for each activity is determined independently from other activities. For each piece of equipment assigned to an activity, an hourly ownership cost rate equal to the weekly rental cost divided by 40 hours is assumed. This figure is used so that the estimate will not be too easy to meet simply by renting all equipment on a daily basis, which would be the case if daily rental rates were used in the estimate, but will not be impossible to meet which would be the case if actual ownership costs were used. Actual ownership costs are used for those units not available for rental. Hourly operating costs and operator's wages, together with the hourly ownership costs, are charged for every unit assumed to be assigned to an activity for a time equal to the estimated duration of the activity for a time equal to the estimated duration of the activity, determined as explained above. Thus an independent cost for each activity is determined, not including any idle time or breakdowns. A crane on shore and a master mechanic as required by the project are also charged for 12 weeks. The sum of all activity costs and the shore crane and master mechanic costs is taken as the estimated project cost. The figure is $149,006.

Plan for Construction

Before the beginning play, the entire construction of the project is planned. The general plan for construction is to attempt to minimize the cost of the major equipment required for the project. To do this, the main equipment requirements are identified. Resource leveling is performed to reduce demands for these units to a minimum at any time and enable full utilization of these units over the project. The minimum number of units required are then purchased before the project begins. If full utilization can be accomplished, the ownership and operating costs over the project of these few units should be substantially less than the costs of renting such units whenever required. Less important units are to be rented in all cases.

This general plan is applied to the specific requirements of the project in the game. The main equipment requirements identified are cranes, barges, barge propulsion units, and pile hammers. After examining equipment requirements for activities in the project, it is decided to construct the bridge as two symmetrical halves, each consisting of a large pier, a small pier, and an abutment. Resource leveling of cranes, barges, and hammers produced the planned network, shown in Figure 16, for each half of the bridge. This plan emphasizes superstructure erection on the abutment, small pier, and large pier in sequence to minimize requirements for the expensive 90-ton crane, which must be used for superstructure erection. It will be necessary to purchase one pile hammer, one 90-ton crane, one 17.5-ton crane, and four barges with propulsion units for each half of the bridge. The dotted arrows in Figure 16 are equipment constraints. L2 to S1, S2 to L3, L4 to S2, and S4 to A1 constraints are for the pile hammer, which will work the large pier, then the small pier during clamshell excavation on the large pier, then complete the large pier, then complete the small pier, and finally drive piles on the abutment. L12 to A1, A3 to S14, and S15 to L14 are for the 90-ton crane, which will work the large pier up to concrete pouring, then the entire abutment, and then pile extraction and superstructure erection on the small and large piers in that order. S13 to L13 constraint is for the 17.5-ton crane, which will pour concrete on the large pier after pouring concrete on the small pier. Some shifting of

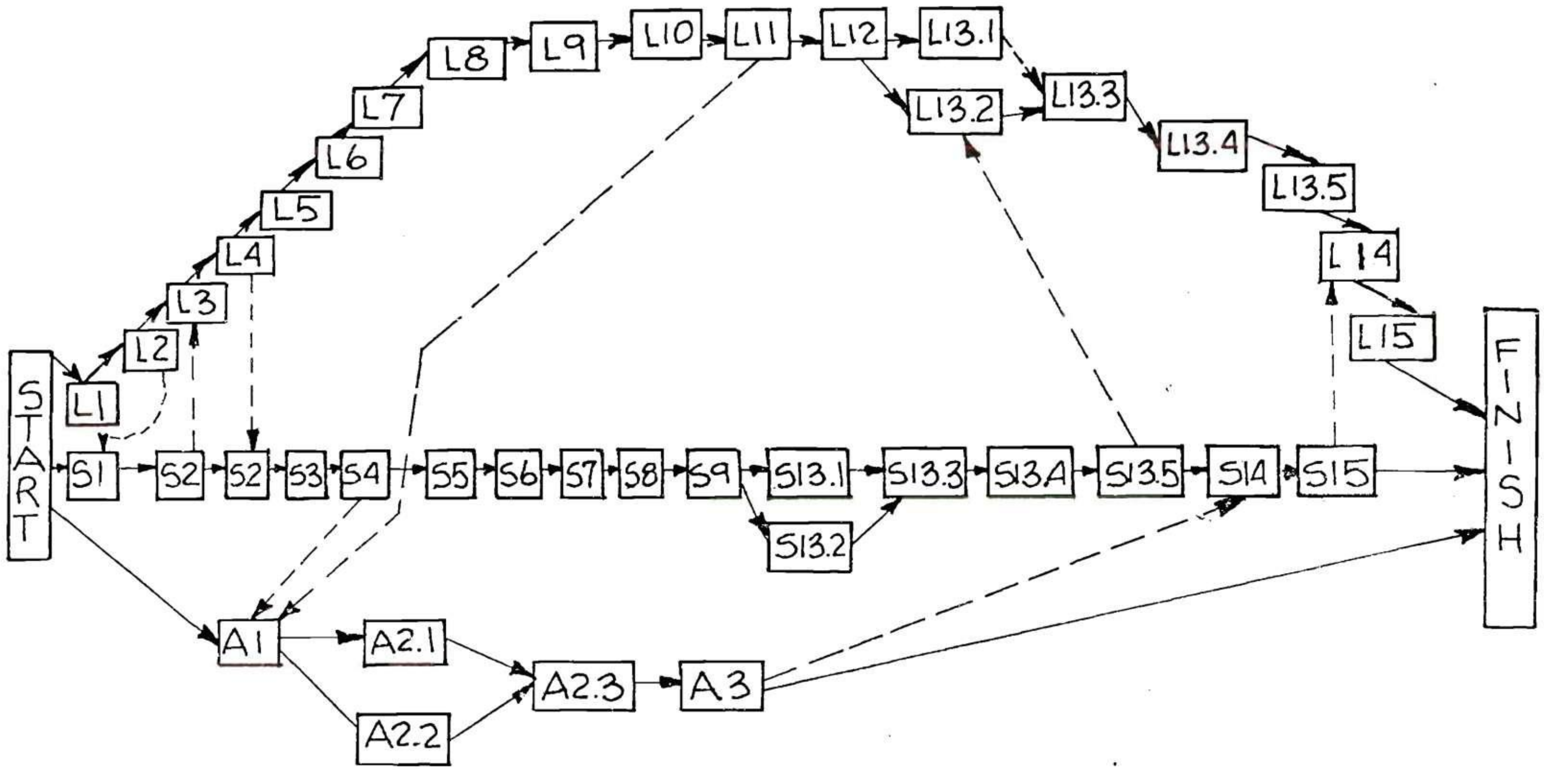


Figure 16. Planned Network for Example

the small and large cranes is anticipated between the large and small piers as different activities arise.

Projected finish times based on the plan for activities on either half of the bridge are shown in Table 31. The times are expressed as working hours from the start of the project. Activity durations used are the estimated durations from the preliminary estimate given above. The latest projected finish time is 525.5 hours for L15, which is 45.5 hours over the imposed 12 week limit. It is expected that this time will be made up by using larger units and more time-saving methods than those assumed for the preliminary estimate.

Decisions and Results During Play

Tables 32-47 present play as it occurred. Tables 32-33 show all purchases and rentals made in accordance with the plan for the entire project. Tables 36-47 show all activities worked, equipment assignments, weather effects, breakdowns, and progress for every week of play. Tables 34-35 are summaries of costs for all units, purchased and rented, for the entire project. The interested reader can reconstruct the entire sequence of play in this example from these tables. The following is a general description of what occurs in the example.

Before play, five cranes are purchased, two for each half of the bridge as planned, and one 29-ton crane for the shore as required by the game. Two of these cranes are purchased used.

Play occurs for 12 periods, representing 12 weeks beginning on October 1, 1973. During the first two periods of play there are some unplanned delays because the 17.5-ton cranes purchased are not big enough to handle sheet piles or clamshell excavation. Thus work must proceed alternately on large and small piers for the most part. However, use of a large DE-30 hammer for pile driving and use of the 29-ton crane to help out with sheet pile driving while the 17.5-ton cranes are idle, speeds work. Weather in early October is excellent. Thus work is well ahead of schedule.

During weeks three, four, five, and six the plan is followed and all cranes can be used. Ninety-ton and 17.5-ton cranes are shifted among large and small piers and the abutments to best use their capabilities, introducing some minor delays but achieving near full utilization. For example, during week four the least busy crane works 36.4 hours. Some minor breakdowns occur. Weather is good until week five but then worsens, as expected. Use of time-saving methods keep the project ahead of schedule. For example, on both halves of the bridge, abutment superstructure erection is completed, with the latest finish of this activity occurring at time 226, vs. a planned finish time of 324.7.

During weeks seven, eight, and nine delays occur when pouring of concrete on large piers cannot proceed concurrently with superstructure erection on small piers. This is due to a shortage of barge propulsion units that was not anticipated during planning. Weather productivity is only fair. However, during these weeks all activities remaining are finished except sheet pile extraction and superstructure erection on the two large piers. Pouring of concrete on large piers is finished by time 366.6 vs. a planned finish time of 422.9. The project seems to be enough ahead of schedule to complete the large piers by the end of 12 weeks.

Unfortunately, in the final three weeks disaster strikes. During week ten the only major breakdown of the project, 16 hours duration, and the longest minor breakdown of the project, eight hours duration, occur. Additional hours of 5.1 are lost to bad weather. A close finish is anticipated. During week 11 bad weather comes and productivity drops below 50 percent, putting the project behind schedule. The project is put on double shift in a desperate attempt to recoup during week 12, but bad weather drops productivity to 28.1 percent. The project is uncompleted as time runs out, and the game is lost.

In retrospect, the loss was due to poor planning. Not enough safety margin was provided in the plans to cover probable losses in productivity during December. The plan worked well for control of costs. At the end of 12 weeks, costs were only \$139,870, more than \$9,000 less than the estimate. This was in spite of the wasteful double shift operations of week 12 during bad weather. Judicious use of rented equipment to speed work earlier, or perhaps double shifts or overtime work during good October weather, might have completed the project on time, at planned cost or below.

Procedure of Play for Week Four

The procedure of play for week four will be examined in detail as an example. The play follows the "Sequence of Play" in Appendix A.

The activities to be worked and equipment assignments for week four are determined using a weekly activity network, shown in Figure 17. All planned shifts of equipment to new locations during the week can be seen as dotted constraint arrows in Figure 17. All equipment assignments for the week are shown in Table 39. On side one of the symmetrical

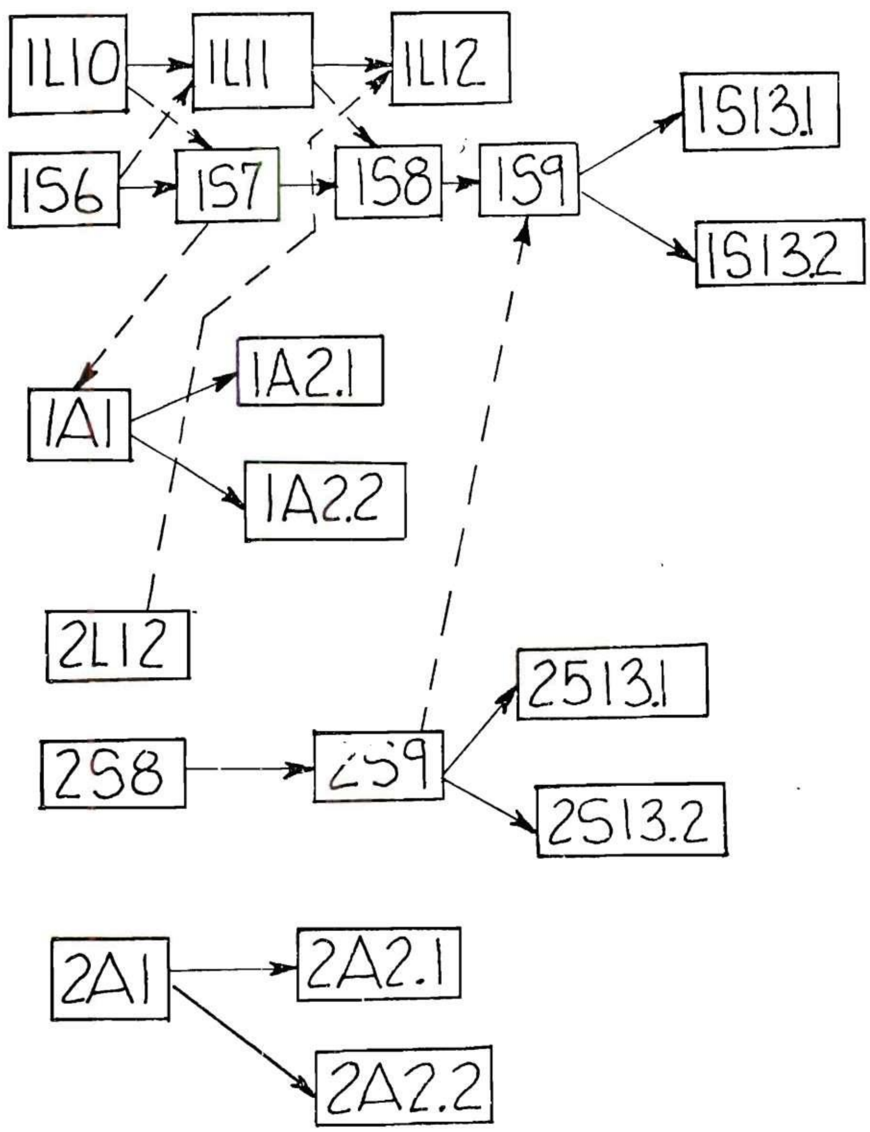


Figure 17. Weekly Network for Week Four

bridge, the bracing installation on the large pier (L10) and the pile cap on the small pier (1S6) will be completed from the previous week. Then the 17.5-ton crane used on 1S6 shifts to the large pier for 1L11, while the 90-ton crane used on 1L10 shifts to 1S7. Both activities 1L11 and 1S7 involve bracing installation. The larger crane on the small pier permits installation of bracing as a unit. This saves time so that the smaller pier superstructure can be completed before the large pier superstructure erection must begin, in accordance with the original plan. After these two activities, the 17.5-ton crane shifts back to the small pier for 1S8 since a large crane will no longer increase productivity there. The 90-ton crane shifts to the abutment to drive H-piles (1A1). Construction on the large pier is held up after dewatering to permit abutment construction to proceed, in accordance with the plan. On side two of the symmetrical bridge, no equipment shifts are necessary. Dewatering is completed on the large pier (2L12) while abutment construction proceeds using a 90-ton crane, and small pier construction using a 17.5-ton crane. The same pumps are used on 1L12 and 2L12, and on 1S9 and 2S9, causing the constraints between those activities.

Following equipment assignments, progress and costs for week four are calculated and recorded. Base times for activities are taken from the Activity Information in Appendix A. Weather is found to be good, with no time lost and all productivity factors being 100 percent. A check on all activities for breakdowns is made, using the breakdown probabilities for all units previously recorded on cards. Minor breakdowns on 2L12 and 2A1 occur, of durations seven hours and two hours respectively involving a rented submersible pump and a DE-30 pile hammer. The durations of those activities are increased accordingly. The weekly network is then used to calculate hours worked and finish times or percent complete for all activities, and progress is recorded on the form provided for that purpose, shown in Table 39. For example, on side one of the bridge, 1S9 finishes at time 144.1, allowing 1S13.1 and 1S13.2 to begin. 1S13.2 has a duration of 11 hours, and so is 100 percent complete with finish time 155.1. 1S13.1, however, has a duration of 40 hours. It is worked for the remainder of the week, 15.9 hours, since week four ends at time 160; and recorded as 15.9/40, or 40 percent complete. Hours worked for all units for this week are taken from Table 39 and recorded on another form shown in Table 49. Finally, the costs shown in Table 48 are computed using cost rates previously calculated and recorded for all equipment.

Table 31. Planned Finish Times for Example

Activity	Planned Finish Time (Working Hours from Start)
L1	9.8
L2	31.3
L3	52.8
L4	108.0
L5	112.9
L6	128.0
L7	147.7
L8	151.4
L9	154.4
L10	169.1
L11	183.8
L12	201.2
L13	422.9
L14	440.3
L15	525.5
S1	41.1
S2	114.8
S3	129.2
S4	184.4
S5	189.3
S6	204.4
S7	224.1
S8	227.8
S9	229.3
S13	301.9
S14	339.9
S15	425.1
A1	246.7
A2	283.3
A3	324.7

Table 32. Form A1, Example

Unit Purchased	Price	Age (years)	First Week	Last Week
(1) 90-ton Crane	$280,000	New	1	12
(2) 90-ton Crane	280,000	New	1	12
(3) 17.5-ton Crane	52,000	New	1	8
(4) 17.5-ton Crane	39,000	3	1	10
(5) 29-ton Crane	40,833	5	1	7
(6) DE-30 Hammer	18,300	New	1	3
(7) DE-30 Hammer	18,300	New	1	3
(8-11) 40 x 30 Barges	21,000 (ea)	New	1	12
(12-13) 70 x 40 Barges	45,800 (ea)	New	1	12
(14-15) Barge Propulsion Units	15,000 (ea)	New	1	12
(18) 30 x 10 Barge	6,450	New	1	1
(19-20) Barge Propulsion Units	15,000 (ea)	New	2	12
(21-22) 40 x 30 Barges	21,000 (ea)	New	2	6
(23-34) Hydraulic Jacks	786 (ea)	New	3	12

Table 33. Form A2, Example

Unit Rented	First Week	Last Week
R1) 20' Hammer Leads	1	2
R2) 20' Hammer Leads	1	2
R3) 172,190 lbs Sheet pile	1	6
R4) 172,190 lbs Sheet pile	1	6
R5) 2 yd Clamshell bucket	1	2
R6) 2 yd Clamshell bucket	1	2
R7) 70' Hammer Leads	1	3
R8) 70' Hammer Leads	1	3
R9) 258,285 lbs Sheet pile	2	10
R10) 258,285 lbs Sheet pile	2	10
R11) 1 yd Clamshell bucket	2	2
R12-19) 2 yd Concrete buckets	2	6
R20) 6" centrifugal pump	3	5
R21) 3" submersible pump	3	5
R22, 23) 30' x 20' x 10' pier forms	4	6
R24, 25) Abutment forms	4	5
R26-33) 2 yd Concrete buckets	5	5
R34) 400A extractor	6	10
R35) 400A extractor	6	10
R36) 600 CFM compressor	6	10
R37) 600 CFM compressor	6	10
R38, 39) 50' x 20' x 10' pier forms	6	9

Table 34. Cost Summary for Purchased Units for Example

	Machine	Hrs Worked	Hrs Field Repair	Hrs Shop Repair	Own Cost	Op Cost	Oper Wages	Rep Cost	Total Cost
1)	90-ton Crane	468.2	8	0	$14,976	$2,566	$6,891	$1,247	$25,580
2)	90-ton Crane	463.9	12	0	14,976	2,542	6,886	1,122	25,526
3)	17.5-ton Crane	254.2	11	0	1,408	404	3,837	418	6,067
4)	17.5-ton Crane	363.5	0	0	1,330	578	5,260	0	7,168
5)	29-ton Crane	226.2	0	0	1,162	398	3,273	0	4,833
6)	DE-30 Hammer	102.6	15	0	664	68	0	401	1,133
7)	DE-30 Hammer	102.0	0	0	664	67	0	0	731
8-11)	Barges	NA	0	0	1,295	0	0	0	1,295
12-13)	Barges	NA	0	0	1,412	0	0	0	1,412
14)	BPU	390.2	4	0	802	1,615	3,299	50	5,766
15)	BPU	371.6	6	0	802	1,538	3,110	75	5,525
18)	Barge	NA	0	0	8	0	0	0	8
19)	BPU	252.9	3	16	735	1,047	2,142	238	4,162
20)	BPU	263.9	0	0	735	1,093	2,209	0	4,037
21)	Barge	NA	0	0	108	0	0	0	108
22)	Barge	NA	0	0	54	0	0	0	54
23-34)	Jacks	NA	0	0	580	0	0	0	580
	Total								$93,985

Master Mechanic: $8.87 x 465.4 = $4,128

Total Job Expenditure = $139,870 (Includes Rental Costs from Table 35)

Table 35. Cost Summary for Rented Units for Example

Machine		Hrs Worked	Time Charged			Rent Cost	Op Cost	Oper Wages	Total Cost
			Day	Week	Month				
R1)	20' Leads	NA	1	1	0	$ 42	$	$	$ 42
R2)	20' Leads	NA	0	1	0	30			30
R3)	Sheet pile	NA	0	0	2	5,854			5,854
R4)	Sheet pile	NA	0	0	2	5.854			5,854
R5)	Clamshell	NA	4	0	0	144			144
R6)	Clamshell	NA	1	0	0	36			36
R7)	70' Leads	NA	0	3	0	261			261
R8)	70' Leads	NA	3	2	0	261			261
R9)	Sheet pile	NA	0	0	3	9,557			9,557
R10)	Sheet pile	NA	0	0	3	9,557			9,557
R12-13)	Concrete buckets	NA	5	1	0	276			276
R14-15)	Concrete buckets	NA	4	1	0	242			242
R16-19)	Concrete buckets	NA	5	0	0	272			272
R20)	6" pump	7.8	4	0	0	132	10	42	184
R21)	3" pump	19.1	3	1	0	125	1	104	230
R22)	Pier forms	NA	0	0	1	956			956
R23)	Pier forms	NA	0	0	1	956			956
R24-25)	Abt. forms	NA	0	0	1	1,656			1,656
R26-33)	Concrete buckets	NA	1	0	0	136			136
R34)	Extractor	NA	6	0	0	260			260
R35)	Extractor	NA	4	0	0	260			260
R36)	Compressor	31.8	6	0	0	600	101	211	912
R37)	Compressor	23.7	4	0	0	400	75	158	633
R38-39)	Pier forms	NA	0	0	1	3,188			3,188
	Total								$41,757

Table 36. Form D, Week 1 of Example

Activity	Reg Hrs	Units Used	Wthr Produc (%)	BD Delays	% Complete	Finish Time
1L1	8.2	6, 3, 8, 14, R1	.98		100	8.2
1L2	12.3	8, 10, 14, 6, 1, 12, R1, R3	.98	7	100	27.5
1L3	8.2	1, 12, R5	.98	2	100	35.7
1S1	8.2	6, 3, 8, 14, R1	.98	2	100	37.7
1S2	2.3	8, 10, 14, 6, 1, 12, R1, R3, 5, 11	.98		31	
2L1	8.7	7, 4, 9, 15, R2	.98		100	8.2
2L2	5.0	9, 18, 15, 7, R4, 2, 13, 5, 11, R2	.98		100	13.2
2L3	6.2	2, 13, R6	.98		100	19.4
2L4	7.2	9, 15, 7, 2, 13 R8	.98		88	
2S1	8.2	7, 4, 9, 15, R2	.98		100	21.4
2S2	11.4	9, 18, 15, 7, 2, 13, R2, R4	.98		100	32.8

Table 37. Form D, Week 2 of Example

Activity	Reg Hrs	Units Used	Wthr Produc (%)	BD Delays	% Complete	Finish Time
1L4	23.0	8, 14, 6, 1, 12, R7	100		100	25.8
1S2	2.8	8, 10, 14, 6, 1, 12, 5, 10, R1	100		100	2.8
1S3	17.5	10, 5, R11	100		100	20.3
1S4	10.2	8, 14, 6, 1, 12, R7	100	9	44	
1L5	4.0	8, 14, 1, 12	100		100	29.8
1L6	10.2	10, 19, 21, 3, R12-15	100		67	
1L4	2.8	9, 15, 7, 2, 13, R8	100		100	2.8
1S3	9.2	2, 13, R5	100		100	16.0
1S4	.15	2, 13, 9, 15, 7, R8	100		65	
1L5	4.0	9, 15, 2, 13	100		100	6.8
1L6	15.2	11, 20, 4, 22, R16-19	100		100	22.0
1L7	16.0	4, 22, 11, 20	100		100	39.0
1L8	1.0	4, 22, 11, 20	100		33	

Table 38. Form D, Week 3 of Example

Activity	Reg Hrs	Units Used	Wthr Produc (%)	BD Delays	% Complete	Finish Time
1L5	5.2	10, 19, 21, 3, R12-15	96.5		100	5.2
1L7	16.6	10, 19, 21, 3	96.5	3	100	21.8
1L8	3.1	10, 19, 12, 1	96.5		100	28.9
1L9	2.5	R20	96.5		100	31.4
1L10	8.6	12, 1	96.5		69	
1S4	15.7	8, 14, 6, 1, 12, R7	96.5	6	100	21.7
1S5	4.1	8, 19, 1, 12	96.5		100	25.8
1S6	14.2	8, 14, 21, 3, R12-15	96.5		90	
2L8	2.1	5, 22, 11, 20	96.5		100	2.1
2L9	2.5	R20	96.5		100	4.6
2L10	12.4	2, 13	96.5		100	24.8
2L11	4.1	2, 13, 11, 20	96.5		100	28.9
2L12	11.1	R21	96.5		43	
2S4	8.3	2, 13, 9, 15, 7, R8	96.5		100	8.3
2S5	4.1	9, 15, 2, 13	96.5		100	12.4
2S6	15.8	5, 22, 9, 15, R16-19	96.5		100	20.7
2S7	8.3	2, 13, 9, 15	96.5		100	37.2
2S8	2.8	5, 22, 9, 15	96.5		90	

Table 39. Form D, Week 4 of Example

Activity	Reg Hrs	Units Used	Wthr Produc (%)	BD Delays	% Complete	Finish Time
1L10	3.7	1, 12	100		100	3.7
1L11	16.0	10, 19, 21, 3	100		100	19.7
1L12	18.8	R21	100		75	
1S6	1.5	8, 14, 21, 3, R12-15	100		100	1.5
1S7	8.0	8, 14, 1, 12	100		100	11.7
1S8	3.0	8, 14, 3, 21	100		100	22.7
1S9	1.4	R20	100		100	24.1
1S13.1	15.9	3	100		40	
1S13.2	11.0	3(con)	100		100	35.1
1A1	19.9	1, 6, R7	100		100	31.6
1A2.1	8.4	1	100		38	
1A2.2	8.4	1(con)	100		93	
2L12	14.2	R21	100	7	100	21.2
2S8	.3	5, 22, 9, 15	100		100	.3
2S9	1.4	R20	100			1.7
2S13.1	38.3	5	100		96	
2S13.2	11.0	5(con)	100		100	40.0
2A1	19.9	2, 7, R8	100	2	100	21.9
2A2.1	20.1	2	100		91	
2A2.2	9.0	2(con)	100		100	40.0

Table 40. Form D, Week 5 of Example

Activity	Reg Hrs	Units Used	Wthr Produc (%)	BD Delays	% Complete	Finish Time
1L12	8.0	R21	.78		100	8.0
1S13.1	30.8	3	.78	8	100	38.8
1S13.3	1.2	8, 19, 1, 12	.78		100	40.0
1A2.1	6.7	1(con)	.78		100	6.7
1A2.2	7.5	1	.78		100	7.5
1A2.3	2.6	1, R12	.78		100	10.1
1A2.4	4.5	1	.78		100	14.6
1A3	24.2	1, 23, 24	.75		55	
2S13.1	2.0	2	.78		100	2.0
2S13.3	1.3	7, 15, 2, 13	.78		100	3.3
2S13.4	6.0	2, 13, 9, 15, 11, 20, R26-33	.78		100	9.3
2S13.5	6.4	2, 13, 9	.78		100	15.7
2A2.1	2.5	5	.78		100	2.5
2A2.3	2.6	5, R13	.78		100	5.1
2A2.4	4.5	5	.78		100	9.6
2A3	24.3	2, 25, 26	.75		55	
L13.1	30.4	5	.78		35	

Table 41. Form D, Week 6 of Example

Activity	Reg Hrs	Units Used	Wthr Produc (%)	BD Delays	% Complete	Finish Time
1S13.4	5.8	3, 21, 8, 14, 10, 10, R12-19	81.4		100	5.8
1S13.5	6.1	1, 12, 8	81.4		100	11.9
1S14	14.0	1, 12, 8, 14, R34, R35	74.5		96.5	
1A3	19.9	1, 23, 24	74.5		100	26.0
1L13.1	30.2	3	81.4	4	36.1	
1L13.2	22.1	3(con)	81.4		100	27.9
2L13.1	40.0	5	81.4		73.7	
2L13.2	22.1	5(con)	81.4		100	22.1
2S14	14.5	2, 13, 9, 15, R35, R37	74.5		100	37.2
2S15	2.8	2, 13, 9, 15, 20, 31, 34	74.5		3.1	
2A3	20.7	2, 25, 26	74.5	2	100	22.7

Table 42. Form D, Week 7 of Example

Activity	Reg Hrs	Units Used	Wthr Produc (%)	BD Delays	% Complete	Finish Time
1S14	3.1	1, 12, 8, 14, R34, R36	81.9		100	3.1
1S15	36.9	1, 12, 8, 14, 19, 27-30	81.9		44.5	
1L13.1	35.0	3	84.2	5	80.0	
2S15	33.0	2, 13, 9, 15, 20, 31-34	81.9	7	42.8	
L13.1	21.2	5	84.2		100	21.2

Table 43. Form D, Week 8 of Example

Activity	Reg Hrs	Units Used	Wthr Produc (%)	BD Delays	% Complete	Finish Time
1L13.1	14.3	3	95.3		100	14.3
1S15	32.0	1, 12, 8, 14, 19, 27-30	93.3		88.4	
2S15	32.0	2, 13, 9, 15, 20, 31-34	93.3		86.7	

Table 44. Form D, Week 9 of Example

Activity	Reg Hrs	Units Used	Wthr Produc (%)	BD Delays	% Complete	Finish Time
1S15	11.7	1, 12, 8, 14, 19, 27-30	.674		100	11.7
1L13.3	1.3	1, 12, 8, 14	.798		100	13.0
1L13.4	9.6	1, 12, 8, 14, 10, 19, R12-19, R39	.798	4	100	26.6
1L13.5	10.0	1, 12, 2, 14, R39	.798		100	36.6
1L14	3.4	1, 12, 8, 14, R34, R36	.674		21.3	
2S15	13.4	2, 13, 9, 15, 20, 31-34	.674		100	13.4
2L13.3	1.3	9, 15, 2, 12, R38	.798		100	14.7
2L13.4	9.6	2, 13, 9, 15, 11, 20, 26-33, R38	.798		100	24.3
2L13.5	10.0	2, 13, 9, 15, R38	.798		100	34.3
2L14	5.7	2, 13, 9, 15, R35, R37	.674		35.6	

Table 45. Form D, Week 10 of Example

Activity	Reg Hrs	Units Used	Wthr Produc (%)	BD Delays	% Complete	Finish Time
1L14	11.3	1, 12, 8, 14, R34, R36	.755		100	11.3
1L15	7.6	1, 12, 8, 14, 19, 27-30	.755	16	8.4	
2L14	9.2	2, 13, 9, 15, R35, R37	.755	8	100	17.2
2L15	17.7	2, 13, 9, 15, 20, 21-34	.755		19.6	

Table 46. Form D, Week 11 of Example

Activity	Reg Hrs	Units Used	Wthr Produc (%)	BD Delays	% Complete	Finish Time
1L15	40.0	1, 12, 8, 14, 19, 27-30	.490		37.2	
2L15	40.0	2, 13, 9, 15, 20, 31-34	.490		48.4	

Table 47. Form D, Week 12 of Example

Activity	Reg Hrs	Units Used	Wthr Produc (%)	BD Delays	% Complete	Finish Time
1L15	80.0	1, 12, 8, 14, 19, 27-30	.281		70.3	
2L15	80.0	2, 13, 9, 15, 20, 31-34	.281		81.4	

Table 48. Form C, Week 4 of Example

Machine		Hrs Worked	Hrs Field Repair	Hrs Shop Repair	Own/ Rent Cost	Op Cost	Oper Wages	Rep Cost	Total Cost
R21)	3" pump	33.0	7	0	$ 62	$ 1	$219	$ 0	$ 280
1)	90-ton Crane	40.0	0	0	1,248	219	579	0	2,046
2)	90-ton Crane	40.0	0	0	1,248	219	579	0	2,046
3)	17.5-ton Crane	36.4	0	0	176	58	527	0	761
4)	17.5-ton Crane	40.0	0	0	133	64	579	0	776
5)	29-ton Crane	38.6	0	0	166	68	559	0	793
6)	DE-30 Hammer	19.9	0	0	166	13	0	0	179
7)	DE-30 Hammer	19.9	2	0	166	13	0	54	233
8-11) 21-22)	Barges	NA	0	0	162	0	0	0	162
12-13)	Barges	NA	0	0	118	0	0	0	118
18)	Barge	NA	0	0	8	0	0	0	8
14)	BPU	12.5	0	0	67	52	105	0	224
15)	BPU	.3	0	0	67	1	3	0	71
19,20)	BPU	0	0	0	134	0	0	0	134
R7)	70' Leads	19.9			87				87
R8)	70' Leads	19.9			87				87
R12-15)	2 yr con. buck.	1.5			68				
R20)	6" pump	2.8			33	3	15	0	51
R3)	Sheet pile	1 wk							
R4)	Sheet pile	1 wk							
R9)	Sheet pile	1 wk							
R10)	Sheet pile	1 wk							
R22)	Pier forms 30'	15.9							
R23)	Pier forms 30'	15.9							
R24)	Abut. forms	8.4							
R25)	Abut. forms	9.0							

APPENDIX C

SOURCES OF ACTIVITY DURATIONS FOR THE PROJECT MODEL

Times given in the "Project Model" to complete activities with any set of assigned equipment were designed to accurately reflect the effects of using different sets of equipment on any activity. Times are related to the characteristics of assigned units of equipment and the number of assigned units. These times were derived as follows.

Times for pile driving operations (L or S 2, 4, 14 and A1)* were related to characteristics of hammers assigned. In each case, a typical productivity for the operation was obtained from estimating guides[37] and contractors' estimates. Manufacturers' hammer application guides[38] were used to determine the hammer size most suitable for the job. This size was assigned the typical productivity. Productivities for other hammers varied linearly with the ratio of their effective energy per minute to that of the most suitable hammer. This approximation of productivities is not useful for predicting actual results. However, it can generate results which will realistically reflect a possible variation in productivities on an actual job with specific soil conditions, because hammer productivity varies widely for different conditions, but for any specific conditions is

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*See "Project Model," Appendix A, p. 46, for numbering and descriptions of activities.

largely dependent on effective energy per minute delivered to the pile.[39] An example of a pile driving activity is pier activity 4, "Driving H-piles for Pier Foundation." The total job includes 50 piles, each to be driven 50', or a total of 2500 lf. Typical productivity was determined to be 500 lf per day. The hammer size recommended for driving 12-inch steel H-piles 50' was a hammer capable of delivering 375,000 effective ft lbs per minute. The hours for the job using any hammer are then 40 hours (2500 lf at 500 lf per day) times the ratio of 375,000 to the effective ft lbs per minute of the hammer used.

Time for clamshell excavation (L or S 3) is based on an assumed productivity of 30 one-cubic yard bucketfuls per hour. This figure was obtained from estimating guides.[40,41] A bucket factor is used to account for the higher cycles per hour that a lighter machine can achieve. These factors were estimated from comparative figures given in an estimating guide.[42]

Times for concreting operations (L or S 6, 13, and A2) are based on productivities for several subactivities. Productivities for tying reinforcing steel and erecting and stripping forms were estimated from estimating guides[43] and contractors' estimates. Figures used were 4400 lbs per day for tying reinforcing steel, 1300 SF per day for form erection, and 3200 SF per day for stripping and cleaning forms. Productivity for placing barge delivered concrete was estimated from documented examples[44,45] and contractors' estimates. It was assumed that any one barge would have a cycle time of four minutes travel, plus four minutes for loading and dumping each concrete bucket on the barge. Maximum amount of concrete placed was further limited to 30 bucketfuls per hour for the crane. From these figures, time to place concrete can be calculated.

Times for dewatering (L or S 9, 12) are based on averaging of pump performance predicted by manufacturers for conditions of pumping at the start and at the finish of each dewatering activity. Friction heads are estimated from length of hose and approximate velocities of pumping.

Times for superstructure erection (L or S 15, A3) were estimated from documented examples.[46,47]

Times for specialized activities (L or S 5, 7, 8, 10, 11) not treated in detail in references are based on contractors' estimates.

APPENDIX D

SOURCES OF EQUIPMENT MARKET AND UNION HALL COMPONENTS

Specifications for equipment in the Equipment Market come from manufacturers' literature. Prices for new equipment were obtained from equipment dealers, or in some cases from estimating guides. Prices for used equipment are determined from prices of new equipment, using straight line depreciation as explained in Peurifoy.[14] Rental rates given in the Equipment Market were obtained from associated equipment distributors.[15]

Information in the Union Hall component is taken from actual labor agreements,[16] somewhat altered for simplicity.

APPENDIX E

TECHNIQUES FOR CALCULATING WEATHER EFFECTS

The simulated weather during any period of play affects the work completed in two ways. First, the number of hours actually available for work during the period is determined by weather. Second, the weather affects productivities on all work. This double effect idea for simulating weather is borrowed from Halpin and Woodhead.[48]

The number of hours available for work during a week is affected by wind chill temperature and rain. The base number of hours available depends on working arrangements, either regular, overtime, or double shift. Then, for each day when average wind chill temperature is below 0°F, work is assumed to be impossible[49] and the hours for that day are subtracted from the base number available. Rainfall is assumed to prevent work only when in the form of a thunderstorm, indicating steady rain. Contractors interviewed indicated that work can proceed at reduced productivities when precipitation occurs as heavy fog. Number of hours lost during a thunderstorm is determined from rainfall productivity factors developed by Russo.[50] On a day when a thunderstorm occurs, loss in productivity is assumed to be due to lost time, so a number of hours equal to base hours available on that day reduced by (100% minus the productivity factor corresponding to the inches of rain from the storm) is subtracted from the base time for the week. Factors and steps for the calculation of time available for any week are given on p. 86.

The productivity for work during any week is calculated by averaging productivity factors for each day not already omitted because of weather. On any day productivity factors are determined for wind chill temperature and rainfall. Productivity for wind chill equivalent temperatures below 60°F is determined from a simple formula based on previous research[51] and contractors' estimates. Productivity factor for rainfall is the same as the one used to determine time lost during thunderstorms, but is applied only when precipitation is in the form of heavy fog which would permit work at reduced productivities. In addition, there are special productivity factors for temperatures below 32°F on concreting activities[52] and for wind on sheet pile operations and superstructure erection from contractors' estimates. The productivity factors of each type are averaged for all available days during the week to get weather productivity factors for the week. Productivity on any activity is then taken as the product of the applicable productivity factors. Factors and steps for productivity calculations are given on p. 86.

APPENDIX F

SOURCES OF COST AND BREAKDOWN INFORMATION

Ownership Costs

These costs include depreciation; interest, insurance, taxes, and storage; and, for rented equipment, rental payments.

Depreciation for purchased equipment is charged at a weekly rate for any week when the equipment is on the project. The rate is calculated using the Double Declining Balance Method for equipment purchased when new, and Declining Balance Method for used equipment. These methods are used because they will produce higher costs during the earliest years of a unit's service life, when losses in value from wear and obsolescence are greatest.[53] Tables are included for calculation of weekly depreciation costs for any unit. The initial cost, C_o, of the unit is found from the Equipment Market component of the game. Table 24 gives the estimated service life, n, in years for any unit. These values are from Peurifoy.[54] Since Double Declining Balance and Declining Balance methods both apply a constant rate of 2/n or 1/n, respectively, to the unit's value each year to determine depreciation charged during that year, the weekly rate of depreciation is given as follows for a week during the ith year of a unit with a service life n:

$$((2/n)^i/52) \times 100\% \text{ of } C_o \text{ for DDB}$$

$$((1/n)^i/52) \times 100\% \text{ of } C_o \text{ for DB}$$

These values are given for various i and n values in Tables 25 and 26.

For sheet piling and metal forms, service life is difficult to determine. Standard practice for contractors interviewed is to charge 50% of the cost of purchased sheet piles and metal forms to the first job on which they are used.

Interest, insurance, taxes, and storage costs for purchased equipment are charged at a weekly rate based on a rate of 12% per year of the average value of the equipment over its service life.[55] Average value is calculated from the formula

$$\text{Average value} = ((1+n)/2n)C_o$$

where n is the service life of the unit.[56] Table 49 contains interest, insurance, taxes and storage costs as a percent of initial cost, C_o, for various service life values.

For rented equipment, the rental rate given in the Equipment Market replaces depreciation and interest, insurance, taxes and storage costs, as is standard practice.[57]

Operating Costs

These hourly costs include fuel, oil, maintenance, and minor repairs.

Fuel is charged for any mechanized unit at a rate of .06 gallons per horsepower-hour for gasoline engines and .04 gallons per horsepower-hour for diesel engines, reduced by an operating factor assumed to be 66.67%. These values are from Peurifoy[58] and can be found with minor variations elsewhere.[59,60] Fuel costs per gallon of \$.446 for gasoline and \$.396 for diesel fuel were obtained from local offices of oil companies. Fuel cost rates are given for all mechanized units in Table 30.

Oil is charged for any mechanized unit using the formula

$$\text{gallons of oil per hour} = (\text{hp})(.6)(.006)/7.4 + \text{crankcase capacity}/\text{time between changes}$$

This formula is from Peurifoy,[61] and is found with minor variations elsewhere.[62,63] Time between changes was assumed to be 100, 150, or 200 hours depending on maintenance used. Cost per gallon of \$1.778 for oil was obtained from local offices of oil companies. Oil cost rates are given for all mechanized units in Table 30.

Maintenance and minor repairs include the costs of adjustments and repair of minor breakdowns that do not cause immediate shutdown on a job. Such costs are normally included as operating costs.[64] Such costs vary widely according to the amount of money a contractor is willing to invest in maintenance.[65,66] The basic rate used for the game is \$.0035 per horsepower-hour for diesel-powered units and \$.005 per horsepower-hour for gasoline-powered units, given in Peurifoy.[67] These values agree fairly well with maintenance costs estimated in Means.[68] This rate is assumed to cover an average maintenance program, with regular oil changes and lubrication, and fairly regular cleaning and inspection. It is also assumed that one-half of this rate will cover a bare minimum program of maintenance, with only infrequent oil changes and lubrications and little cleaning and inspection; and twice this rate will cover a good maintenance program, with frequent oil changes and lubrications, constant cleaning, and frequent detailed inspections with attempts made to correct deteriorating situations. These assumptions cannot readily be documented because of the wide variance in such costs, and could be adjusted if necessary. No downtime occurs due to maintenance or minor repairs, as this work can be performed while a unit is not being used.[69] Maintenance and minor repair cost rates are given for all units in Table 30.

Duration and Cost of Breakdowns

These breakdowns simulate those that cause immediate shutdown of a unit and require the service of a mechanic. The total hours expected to be lost due to such breakdowns during any year of the life of a unit of equipment is determined from assumptions. The cost of repairs due to such breakdowns is based on a cost rate calculated for any unit of equipment. The timing of breakdowns in the game is generated probabilistically.

Several assumptions and definitions are basic to all procedures described in this section. Times are based on the expected hours of operation per year given for all equipment in Table 24. These figures are from Peurifoy,[70] and represent all the hours a particular type of equipment can be expected to work during a year. Availabilities referred to below represent the percent of the expected hours of operation that a unit of equipment is actually able to work. Downtime refers to the hours that a unit was expected to work but unable to because of breakdown.

The total hours of downtime to be expected due to breakdowns for any unit during any year of its service life is determined as follows. When any unit is first rented or purchased, a value of from 91% to 98% is generated randomly as the availability that unit had during its initial year of operation. This range of values is typical for construction equipment.[71,72,73] Downtime can be expected to increase 10% per year if average maintenance is performed.[74] Downtime is dependent on the level of maintenance performed.[75,76] To reflect this, two assumptions are made. First, high initial availabilities are assigned higher probabilities for generation if good maintenance is used, and vice versa for low maintenance. Second, it is assumed that downtime will increase 15% per year with poor maintenance and 5% per year with good maintenance. These assumed figures can be adjusted if necessary. From initial availability and percent increase in downtime each year, the expected downtime for any year in the service life of a unit can be generated.

The cost of repairs is based on a cost rate calculated for any given unit. It is assumed that major repairs will cost 50% of the initial cost of a unit over the entire service life of the unit, with average maintenance.[77] To apportion this cost over the downtime of the unit throughout its service life, a cost per hour of repairs is calculated as

$$\frac{50\%\ C_o}{\underset{\text{per year}}{(\text{expected hours})}\left(\underset{\text{year 1}}{\%\text{ downtime}} + \underset{\text{year 2}}{\%\text{ downtime}} + \dots + \underset{\text{year n}}{\%\text{ downtime}}\right)}$$

$$= \frac{.5}{\underset{\text{per year}}{(\text{expected hours})}\left(\underset{\text{year 1}}{\text{initial \% downtime}} / 100\right)(1+1.1+1.1^2+\dots+1.1^n}$$

$\times\ 100\%$ of C_o

where C_o is the initial cost and n is the service life in years. Table 29 contains Repair Rate as a percent of C_o from this formula. This same cost rate is charged for repairs on units with poor or good maintenance and correspondingly higher or lower downtime. This results in decreasing total repair costs for increasing amounts of maintenance, reflecting the dependence of total cost of repairs in the life of a unit on the maintenance it receives.[78] No provision is made for varying cost of repairs for use of in-house mechanics rather than outside services, because studies indicate that costs for both cases are similar.[79]

The actual timing of breakdowns is generated probabilistically. Two types of breakdowns are assumed, large and small. Large breakdowns have a duration, randomly determined, of two, three, or four days, and are intended to simulate repairs requiring removal to a shop. Small breakdowns have a duration, randomly determined, of from two to eight hours, and are intended to simulate repairs that can be made in the field. For each activity on which a particular unit is utilized, a random number must be drawn to determine if a breakdown of the unit occurs during that activity, using a calculated probabilities of large and small breakdowns occurring for a given unit on an activity of given duration.* These probabilities are calculated as follows. Let h be the expected hours per year for the unit being considered. The unit is expected to work on K activities with durations X_1, X_2, ..., X_i, ..., X_K hours during the year, so that

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*See p. 129 for procedure for Random Number trials.

$$\sum_{i=1}^{K} X_i = h \quad .$$

Let P_1 be the probability of a small breakdown on an activity of duration one hour, and let P_2 be the probability of a large breakdown on an activity of duration one hour. Assume a linear relationship between duration and breakdown probabilities, so that for an activity of duration X_i the probability of a small breakdown of the unit being considered is P_1X_i, and the probability of a large breakdown of the unit is P_2X_i. Then during a given year the expected number of small breakdowns is

$$P_1(\sum_{i=1}^{K} X_i) \quad ,$$

or P_1h, and the expected number of large breakdowns is

$$P_2(\sum_{i=1}^{K} X_i) \quad ,$$

or P_2h. The expected durations of small and large breakdowns are five hours and three days, respectively, as explained above. Thus the expected hours downtime during a year for the unit being considered is $(5P_1h + 24P_2h)$ using random number trials.* Now the total hours of downtime for the ith year of a unit with service life of n years and average maintenance is h(initial % downtime year 1/100)(1.1^{i-1}) from the assumptions on initial availability and downtime increases

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*See p. 129 for procedure for Random Number trials.

explained above. Equating total hours of downtime with the expected value of total hours of downtime determined using random number trials yields

$$h(5P_1 + 24P_2) = h(\text{initial \% downtime}/100)(1.1^{i-1})$$

It is assumed that $P_1 = 10\ P_2$ to enable solution. This assumption is made as feasible from records studied.[80] Substituting for P_1, the solution is

$$P_2 = (\text{initial \% downtime})(1.1^{i-1})/7400$$

for the ith year of the unit under consideration. For units receiving poor or good maintenance, the solution procedure is the same but "1.1" is replaced by "1.15" or "1.05." Values of $P_2 \div$ (initial % downtime/100) are given in Table 28 so that P_1 and P_2 can be readily calculated for any unit. Procedure for determining breakdowns as play progresses is explained in detail in Appendix A under "Sequence of Play."

APPENDIX G

USE OF NETWORKS IN THE SEQUENCE OF PLAY

During each period in the "Sequence of Play," a weekly activity network for the period is used as the basis for interaction among the various components of the game. These weekly networks are standard Critical Path networks, in "circle" or "precedence" notation. The following explains the use of weekly networks in each step of the "Sequence of Play" section, "Play for a Period."

In Step 1 of "Play for a Period," the weekly network is used to model the player's decisions on activities to be worked and equipment assignments. The activities scheduled are arranged in a miniature network taken from the Critical Path network for the entire project. Constraints are added between activities which are assigned the same equipment. This model of the player's decisions is the basis for the weekly network.

In Step 2 of "Play for a Period," the basic activity durations from the Project Model are assigned to the activities in the weekly network. The network time scale is assumed to represent only the working hours during the week, so that activities can be assumed to continue uninterrupted through the network. This assumption neglects inefficiencies caused by start-ups and shutdowns for each shift, but should not cause too much inaccuracy. Thus the network with basic activity durations serves as a model of what would occur on the project during the week, given the player's decisions, if no adverse conditions affected the work.

In Step 3 the adverse effects of weather are incorporated into the weekly network in two ways. First, the value of total hours available during the week is calculated and used as a limit to the network duration. This simply involves decreasing the basic number of working hours which are to be included in the network time scale by the number of hours when weather makes work impossible. The rationale of using only working hours on the time scale was explained above. Second, the basic activity durations are increased by productivity factors which account for lost productivity in unfavorable weather. Now the network models what would occur given player decisions and weather.

In Step 4 the adverse effects of equipment breakdowns are incorporated into the weekly network. The probability of a breakdown on any activity depends on the hours worked on the activity. So those activities with earliest start times in the network are checked for breakdowns first. Then if breakdowns cause delays which shorten the hours worked on later activities, the probability of breakdown on the later activities will be reduced as it should be. After this step, the weekly network models what will occur on the project under the player's decisions and the simulated environment of the game.

Finally, in Step 5, the weekly network is used to calculate work progress for the period on the project. All final activity durations and the total hours available are known. Early start and finish times are calculated using standard network methods. All activities are assumed to begin at early start times and to continue until early finish time or the end of the hours available, whichever comes first.

Hours worked for all activities and finish times for completed activities are then readily determined. For each uncompleted activity, a percent complete is determined as the ratio of hours worked to the total duration of work in the activity. When the activity is scheduled for a subsequent period, its basic duration determined from the Project Model will be decreased by a factor of 100 percent less the percent complete when it is incorporated in that period's network.

The use of percent complete for uncompleted activities involves a fairly significant assumption. In the game, the same activity can be worked in different weeks using different methods, with different sets of equipment and different basic durations from the Project Model. Thus, use of a percent complete based on hours worked to relate work during separate weeks implies that when an activity is X percent complete timewise using one method, it is also X percent complete timewise using a different method. This assumption is not entirely accurate but should not cause great inaccuracy.

NOTES

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